ANNULAR FLOW OF HERSHEYEL-BULKLEY NON-NEWTONIAN FLUIDS AND MATHEMATICAL MODELLING OF EFFICIENT HOLE CLEANING AT VARIOUS HOLE ANGLES

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Dedicated to my wife - Xuemei Feng

and my son - Feng Gao
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ABSTRACT

The work detailed in this thesis has formed a major part of an industry sponsored project entitled "Drilled Cuttings Transport in Deviated Wells" in the Department of Petroleum Engineering, Heriot-Watt University. The contributions by the author to the project form the basis of this thesis, which includes both the theoretical and experimental investigations into drilled cuttings transport at various hole angles. It is composed of the following major areas:

[1] Annular flow of Herschel-Bulkley fluids: The various flow equations including the fluid velocity profile, viscosity profile, shear stress/shear rate profile for fluid flow of Herschel-Bulkley fluids through concentric annuli without pipe rotation were derived and numerically solved by the author.

[2] Theoretical modelling of the minimum transport velocity (MTV) required for adequate cuttings transport in deviated wells: Two classic concepts - fluid drag force and fluid lift force were successfully used to model the complicated cuttings transport process. Two MTV models were developed by the author for cuttings removal in concentric annuli without pipe rotation. One is the MTV model for cuttings rolling and the other is the MTV model for cuttings suspension.

[3] Development of a new model for cuttings settling velocity in dynamic non-Newtonian drilling fluids: A new technique was proposed by the author to derive the cuttings settling velocity in dynamic non-Newtonian fluids based on the measured MTV for vertical hole cleaning. The cuttings settling velocity data were then used for the development of a new model for cuttings settling velocity at dynamic flow conditions. As well as the predictions of cuttings settling velocity profile and cuttings transport velocity profile across the annulus, this model was also used for the predictions of the MTV for vertical hole cleaning in concentric annuli without pipe rotation.
Cuttings transport/Annular flow experiments: The author contributed to the design and the implementation of an extensive experimental programme to investigate cuttings transport at various hole angles. The experiments were designed to provide the data base required for the development and validation of the MTV models by the author. Annular flow experiments were also designed and conducted to validate the various annular flow equations derived by the author.

Extension of the MTV models: A new method was devised by the author so that the MTV models were able to be extended from concentric annuli without pipe rotation into concentric annuli with pipe rotation and eccentric annuli with/without pipe rotation using the annular flow modelling by Larrucia(87). The effect of drill pipe orbital motion on the MTV, which was from the team work(88), was also incorporated into the MTV models.

The development of the MTV package: The author has developed all the source codes for the development of a new MTV package for hole cleaning design and analysis and has also supervised the detailed development of the package.

Field guidelines: Field guidelines on how to improve drilled cuttings transport in actual drilling operations were developed by the author based on both the theoretical modelling and the experimental results.
NOMENCLATURE
(In consistent units)

a

A constant for the $C_L/N_{Re_p}$ and $C_D/N_{Re_p}$ correlations

$A_a$

Cross-section area of the total annulus defined in Eq. 2.5.1

$A_c$

Cross-section area of the cuttings bed section defined in Eq. 2.5.1

$A_e$

Projected area of the exposed portion of particles

$A_f$

Cross-section area of the fluid flow section defined in Eq. 2.5.1

$A_L$

Projected area of the particle in the direction normal to the flow stream

$A_p$

Projected area of the particle in the direction parallel to the flow stream

b

A coefficient defined in the $C_L/N_{Re_p}$ and $C_D/N_{Re_p}$ correlations

$\text{bea}$

Distance between the inner and the outer wall of an inclined annulus at the lowest position

c

A function of hole angle and fluid velocity defined in Eq. 2.5.8 and Eq. 2.5.9

$C_{\text{ang}}$

Hole Angle Correction factor for the equivalent slip velocity (dimensionless) defined in Eq. 2.5.22

$C_{\text{ann}}$

Annular cuttings concentration at equilibrium conditions

$C_D$

Fluid drag coefficient

$C_{\text{inj}}$

Injected concentration of the drilled cuttings

$C_L$

Fluid lift coefficient

$C_{\text{mwt}}$

Mud Weight Correction factor for the equivalent slip velocity (dimensionless) defined in Eq. 2.5.24 and Eq. 2.5.25

$C_s$

Concentration of solid particles in liquid by volume

$C_{\text{size}}$

Cuttings Size Correction factor for the equivalent slip velocity (dimensionless) defined in Eq. 2.5.23

d_1

Outside diameter of drill pipes

d_2

Wellbore diameter

$D_{\text{DE}}$

Particle diameter, dynamically equivalent to that of a falling sphere

d_{eq}$

Equivalent diameter of an annulus
D_i, i=1,2,3 Characteristic particle dimensions

d_s Diameter of spherical particles

d_sa Surface area equivalent diameter of particles

d_sd Diameter of disk particles

d_e Sieve diameter of drilled cuttings or solid particles

d_v Volume equivalent diameter of non-spherical particles

d_{s50} Cuttings mean diameter

d_{wa} Weighted average sieve diameter of sand or drilled cuttings

e Distance between the axes of the inner and outer tubes

E = 100.0e/r_2, dimensionless eccentricity

f Friction factor for fluid flow in pipes or annuli

F_D Fluid drag force

f_f Fluid friction factor defined in Eq. 2.5.3 and Eq. 2.5.4

F_g Effective gravitational force on settling particles

F_{g_a}, F_{g_v} The gravitational force components, parallel and vertical to the flow directions separately

f_i Friction factor on the interface between the cuttings bed and the fluid flow defined in Eq. 2.5.6 and Eq. 2.5.7

F_L Fluid lift force

f_r Equivalent shear rate coefficient

f_s Friction coefficient between cuttings and the annular wall under "wet" condition

F_T Cuttings transport ratio

f(\theta_i) Coefficient relating particle orientation to fluid drag

g Gravitational constant

g_i Where the subscript i = r, \theta, z

g_p Axial pressure gradient

(g_p)_{min} The minimum pressure gradient to initiate the fluid flow in a circular pipe or concentric annulus
\((g_p)_c^{\text{min}}\) The minimum pressure gradient to initiate the fluid flow in the enlarged region of an eccentric annulus

\((g_p)_n^{\text{min}}\) The minimum pressure gradient to initiate the overall fluid flow in an eccentric annulus

\(K\) Consistency index of power-law fluids

\(L\) Length of the fluid element considered or well length

\(m = \rho_s/\rho_f\)

\(m_1, m_2, m_3\) Coefficients defined in Eq. 2.5.12

\(\text{MTV}\) Minimum transport velocity required for efficient cuttings transport

\(\text{MTV}@2\%\) MTV at 2% cuttings concentration by volume

\(\text{MTV}@C_s\%\) MTV at cuttings concentration of \(C_s\%\) by volume

\(n\) Flow behaviour index of power-law fluids

\(n_1, n_2, n_3\) Coefficients defined in Eq. 2.5.13

\(N_{Re}\) Reynolds number of fluid flow

\(N_{Rep}\) Particle Reynolds number

\(PV\) Plastic viscosity of Bingham Plastic fluids

\(q_f\) Volumetric flow rate of drilling fluids

\(q_s\) Volume of drilled cuttings generated in unit time

\(r\) Radial co-ordinate of the cylindrical co-ordinate system

\(r_0\) Radius of the point of zero shear stress and maximum velocity in annular flow of power-law fluids

\(r_1\) Radius of the inner tube

\(r_2\) Radius of the outer tube

\(r_i\) Inner radius of the unsheared plug in concentric annular flow of non-Newtonian fluid with a yield point

\(r_+\) Outer radius of the unsheared plug in concentric annular flow of non-Newtonian fluid with a yield point

\(\text{ROP}\) Rate of penetration (m/hr)

\(s = 1/n\)

\(S_c\) The perimeter of the cuttings bed section defined in Eq. 2.5.1
\( S_f \)  The perimeter of the fluid flow section defined in Eq. 2.5.1

\( S_i \)  The perimeter of the interface surface between the cuttings and the fluid defined in Eq. 2.5.1

\( v_c \)  Velocity of the cuttings layer defined in Eq. 2.5.5

\( v_{\text{crit}} \)  Critical transport fluid velocity defined by Larsen et al(85)

\( v_{\text{cut}} \)  The average cuttings travel velocity defined by Larsen et al(85)

\( v_d \)  Penetration rate of drilling

\( v_f \)  Average fluid velocity

\( v_i \)  Where the subscript \( i = r, \theta, z \)

\( v_m \)  Mean flow velocity of solid-liquid mixture

\( v_{\text{mt}} \)  Minimum transport velocity (MTV) of solid-liquid mixtures, which is defined as the mean mixture velocity when the critical condition for MTV is achieved

\( v_p \)  Representative velocity of the fluid in the vicinity of the particles

\( v_s \)  Particle settling velocity

\( v_{\text{slip}} \)  Equivalent slip velocity of cuttings corrected for angle, cuttings size and mud weight defined in Eq. 2.5.18

\( \bar{v}_{\text{slip}} \)  Uncorrected equivalent slip velocity of cuttings defined in Eq. 2.5.20 and in Eq. 2.5.21

\( V_s \)  Volume of a solid particle

\( V_t \)  Cutting transport velocity

\( v_* \)  \( = (\tau_f/\rho_f)^{1/2} \), friction velocity of fluid flow

\( v_{\text{mt}} \)  \( = (\tau_{\text{mt}}/\rho_f)^{1/2} \), minimum transport friction velocity defined in Eq. 2.5.10 and in Eq. 2.5.11

\( V_s \)  Volume of a solid particle

\( \gamma \)  Distance between a point in the flow stream and the solid boundary

\( \gamma_p \)  Yield point of Bingham Plastic fluids

\( \alpha_{Ajk} \)  Projected area correction factor of particles

\( \gamma \)  Shear rate of fluids in uni-directional shear flows

\( \gamma_{\text{eq}} \)  Equivalent shear rate for particles settling

\( \gamma_s \)  Shear rate on settling particles

\( \gamma \)  Wall shear rate in annular or pipe flow
\( \delta \) Thickness of the viscous sublayer or buffer layer in turbulent pipe flow

\( \theta \) Angular co-ordinate of the cylindrical co-ordinate system

\( \lambda = r/r_2 \)

\( \lambda_m = r/r_2 \)

\( \lambda_1 = r_1/r_2 = d_1/d_2 \)

\( \lambda_p = \lambda_1 \cdot \lambda = w_p/r_2 \)

\( \mu \) Viscosity of Newtonian fluids

\( \mu_e \) Effective viscosity of non-Newtonian fluids

\( \mu_{eq} \) Equivalent viscosity of non-Newtonian fluids for particle settling

\( \mu_m \) Viscosity of solid-liquid mixtures

\( \mu_p \) Plastic viscosity of Bingham plastic fluids

\( \pi = 3.14159 \ldots \)

\( \Pi_i \) i = 1, 2, 3...Dimensionless groups

\( \rho_f \) Density of the fluid

\( \rho_s \) Density of solid particles or drilled cuttings

\( \tau \) Shear stress of fluids in uni-directional shear flows

\( \tau_c \) The wall shear stress of the cuttings bed section defined in Eq. 2.5.1

\( \tau_f \) The wall shear stress of the fluid flow section defined in Eq. 2.5.1

\( \tau_i \) The wall shear stress of the interface surface defined in Eq. 2.5.1

\( \tau_s \) Shear stress on settling particles

\( \tau_w \) Wall shear stress in annular or pipe flow

\( \tau_{wmt} \) Minimum transport wall shear stress

\( \zeta_n \) Settling velocity equation coefficient

\( \Phi \) Inclination of drilling annuli or hole angle

\( \Phi_c \) Critical angle for cuttings sliding-down when circulation is stopped

\( \psi \) Sphericity of non-spherical particles
Superscript:

\(e\) Eccentric

\(ii\) The subscripts \(i = r, \theta, z\) or \(i = x, y, z\)
CHAPTER 1
INTRODUCTION

One of the major functions of drilling fluids is to transport drilled cuttings from the bottom of the well up to the surface. The efficient removal of drilled cuttings is an essential part of a successful oil well drilling operation. Poor hole cleaning may result in severe problems including:

- High torque and drag;
- Stuck pipe;
- Reduction of rate of penetration;
- Difficulty when running casing and cementing;
- Fracturing the formation;
- Packing off (where cuttings block the annulus preventing circulation).

These will substantially increase the drilling costs and can result in failure to complete the well. As a result, much effort has concentrated on research in this field (1-33,44,45,72,85-87). However, there are still few hard and fast rules as to what fluid properties are required for efficient hole cleaning or to the flow rates which can be employed. The major questions which remain to be answered include:

- Cuttings settling velocity in dynamic drilling fluids;
- The prevention of a cuttings bed formation in inclined wellbores;
- The thickness of the cuttings bed if it exists;
- Reliable models to predict deviated hole cleaning efficiency.

The overall problem is how the various drilling parameters may affect drilled cuttings transport efficiency so that the "controllable" drilling parameters can be adjusted for the minimum build-up of drilled cuttings in the annulus. Unfortunately, our understanding of
these problems is still quite poor after all the effort. For example, will high viscosity fluid in laminar flow or low viscosity fluid in turbulent flow regime give better hole cleaning? Contrary conclusions were obtained even for this "simple" question (See Table 2.9.1). In the present study, an attempt has been made to develop both new experimental techniques and theoretical models for cuttings transport at various hole angles.

In order to have a better understanding of the cuttings transport mechanisms, modelling of non-Newtonian fluid flow through drilling annuli is very important. Due to the fact that Herschel-Bulkley model can effectively describe the rheological properties of actual drilling fluids, the author has derived the various flow equations for concentric annular flow of Herschel-Bulkley fluids, including the velocity profile, shear stress/shear rate profile, fluid effective viscosity profile, and the relationship between flow rate and the pressure gradient.

In the present study, two minimum transport velocities (MTV) required for adequate hole cleaning have been defined to evaluate hole cleaning efficiency at different hole angles. An extensive experimental programme has been carried out to study the effects of the drilling parameters on the MTV i.e. cuttings transport efficiency including the effects of drill pipe orbital motion and drill pipe eccentricity.

A new technique is introduced to experimentally measure cuttings settling velocity at actual flow conditions. The new experimental data have then been used for the model development of particle settling velocity in dynamic flow conditions. The newly proposed cuttings settling velocity model has been used to predict the MTV for vertical hole cleaning and the cuttings transport velocity profile across the entire annular space.

Using the modelling of annular flow of non-Newtonian fluids and the classic concepts of fluid drag force and fluid lift force, two new models have also been developed for deviated hole cleaning efficiency. One is the MTV model for the initiation of cuttings rolling and the other is the MTV model for the initiation of cuttings suspension. These models have been verified using both experimental data and field data from the North Sea.
Finally the application and some field guidelines based on the present study have been developed and summarised. An MTV package for hole cleaning analysis and design has been developed.

As a summary, the thesis has covered the following aspects:

Chapter 2 presents an extensive critical literature review, at which the previous studies in cuttings transport have been discussed and analysed. This is followed by the concept of MTV for efficient cuttings transport as defined in chapter 3. The MTV models using the physical force balance are derived for deviated hole cleaning. The various models describing drilling fluid rheological properties are also discussed.

Chapter 4 discusses the experimental programme, the experimental facilities and procedures. A sieve analysis of actually drilled cuttings from the North Sea is also reported in this chapter.

Chapter 5 presents the experimental results. The various flow patterns for the cuttings movements in the drilling annuli are observed and well defined. The MTV for hole cleaning at different hole angles has been experimentally determined based on the specified flow patterns. The effects of the various drilling parameters on hole cleaning efficiency have been analysed based on the experimental data.

Chapter 6 has reported an extensive theoretical study on annular flow of Herschel-Bulkley fluids. The various flow equations including the fluid velocity profile, fluid viscosity profile and the relationship between flow rate and pressure gradient have been derived and numerically solved, the details of which are presented.

In chapter 7, details of a new technique used to derive the cuttings settling velocity from the MTV in vertical wells are presented. A new model is developed for cuttings settling velocity in dynamic drilling fluids. Procedures have also been developed using the new settling velocity model to predict the MTV for vertical hole cleaning. The new model is also used for the predictions of cuttings settling velocity profile and cuttings transport velocity profile across the entire annular space. Chapter 8 has been devoted to the development of
the MTV models for deviated hole cleaning, including the MTV model for cuttings rolling and the MTV model for cuttings suspension.

In chapter 9, an extensive analysis was carried out using all the available information for the analysis of the various drilling parameters on cuttings transport efficiency. Chapter 10 presents the MTV computer package developed, which has incorporated all the theoretical modelling. The application of the MTV package is also highlighted. Some field guidelines are presented in chapter 11 for the field engineers to effectively adjust the various drilling parameters to achieve good hole cleaning. Finally, in chapter 12, conclusions from the present studies and recommendations for further research were made.
CHAPTER 2
LITERATURE REVIEW
ON DRILLED CUTTINGS TRANSPORT

Since the first paper was published by Piggot\(^1\), a tremendous amount of work on cuttings transport has been carried out by different investigators\(^{(2-33)}\). In this chapter, the up-to-date literature is critically reviewed. The various concepts to define hole cleaning efficiency and the corresponding theoretical considerations are analysed. From the literature review, it is concluded that our present understanding of drilled cuttings transport is far from sufficient. More work needs to be carried out for a better understanding of the cuttings transport process so as to optimise drilling operations, especially while drilling highly deviated wells.

2.1 Introduction

During drilling operations, drilled cuttings need to be continuously transported up to surface by the circulation of a drilling fluid. But, in many cases, it is not achieved. Because the density of the cuttings is usually higher than that of the drilling fluid, drilled cuttings have a tendency of settling downward in the fluid. Therefore, in order to transport the drilled cuttings up to the surface in a vertical well, the fluid velocity must be high enough to overcome the settling velocity of the cuttings. To evaluate vertical hole cleaning efficiency, the use of cuttings settling velocity is obvious. If it is assumed that the average fluid velocity can represent the fluid velocity, the cuttings transport velocity may be expressed as:

\[ v_t = v_f - v_s \]  \hspace{1cm} (2.1.1)

where \( v_f \) is the average fluid velocity; \( v_s \) cuttings settling velocity; and \( v_t \) cuttings transport velocity. Sifferman et al\(^{(7)}\) introduced the concept of “cuttings transport ratio” to evaluate hole cleaning efficiency, which is defined as the ratio of the cuttings transport velocity to the average fluid velocity:
\[ F_T = 1.0 - \frac{v_s}{v_f} \]  

(2.1.2)

It is obvious that the higher the cuttings transport ratio \( F_T \), the higher the fluid carrying capacity. Eqs. 2.1.1 and 2.1.2 show that for a given condition, two parameters dominate vertical hole cleaning efficiency. One is the average fluid velocity \( v_f \) and the other is the cuttings settling velocity \( v_s \). Thus, a better understanding of cuttings settling velocity is the key to the understanding of cuttings transport efficiency. Therefore, numerous methods have been used to experimentally and theoretically study cuttings settling velocity. In this chapter, the various experimental techniques used by previous researchers for the measurement of cuttings settling velocity in different drilling fluids are summarised. However, due to the complexity of this problem, in the opinion of the present author, no reliable model has been available for cuttings settling velocity in dynamic drilling fluids.

In deviated wells, a cuttings bed will be formed on the low-side annular wall. Cuttings settling velocity and cuttings transport ratio are no longer valid for the measure of hole cleaning efficiency. Therefore, new theoretical analysis and experimental techniques have been developed to evaluate cuttings transport efficiency in deviated boreholes. In this chapter, the various studies on cuttings transport in deviated wells are also analysed.

2.2 Cuttings settling velocity in drilling fluids

In the above discussion, the importance of cuttings settling velocity on cuttings transport is highlighted. In this section, a brief review of the various methods for cuttings settling velocity measurements and its theoretical considerations is presented.

2.2.1 Brief review of the theory for particle settling in Newtonian fluids

Before talking about cuttings settling in non-Newtonian drilling fluids, a brief overview is presented for the theory of particle settling in Newtonian fluids because many models for cuttings settling in non-Newtonian drilling fluids were derived based on these basic concepts.

For a spherical particle settling in a Newtonian fluid, the force acting on the particle by the fluid should balance the effective gravitational force of the particle when the terminal
settling velocity $v_s$ is reached. At very low particle Reynolds numbers ($N_{Re_p} < 0.1$) i.e. the so-called creeping flow, based on the simplified Navier-Stokes equation together with the continuity equation and the boundary conditions that all velocity components at the surface of the sphere are zero, Stokes derived the fluid drag force acting on the spherical particle:

$$F_D = 3.0\pi \mu d_s v_s$$  \hspace{1cm} (2.2.1)$$

where $F_D$ is the fluid drag force; $\mu$ the fluid viscosity; $d_s$ diameter of the particle. The general equation for fluid drag force $F_D$ is usually expressed as:

$$F_D = \frac{1}{2} C_D \rho_f v^2 A_p$$  \hspace{1cm} (2.2.2)$$

where $C_D$ is the fluid drag coefficient; $\rho_f$ density of the fluid; and $A_p$ the projected area of the particle in the direction parallel to the flow stream. Equating Eq. 2.2.1 and Eq. 2.2.2, the fluid drag coefficient $C_D$ acting on a spherical particle by a Newtonian fluid at creeping flow is obtained as:

$$C_D = \frac{24.0}{N_{Re_p}} \hspace{1cm} (N_{Re_p} < 0.1)$$  \hspace{1cm} (2.2.3)$$

where $N_{Re_p}$ is defined as the particle Reynolds number for the settling particle:

$$N_{Re_p} = \frac{v_s \cdot d_s \cdot \rho_f}{\mu} \hspace{1cm} (2.2.4)$$

When the particle Reynolds number is in the range of 0.1 and 500, the particle is settling in the transition regime between laminar and turbulent flow. In this case, the fluid drag coefficient $C_D$ may be calculated using Allen’s correlation:

$$C_D = \frac{18.5}{N_{Re_p}^{0.6}} \hspace{1cm} (0.1 \leq N_{Re_p} \leq 500)$$  \hspace{1cm} (2.2.5)$$

In turbulent settling regime, the fluid drag coefficient becomes a constant, which is the so-called Newton’s law:

$$C_D = 0.44 \hspace{1cm} (N_{Re_p} > 500)$$  \hspace{1cm} (2.2.6)$$

The relationship between the drag coefficient and particle Reynolds number is shown in Fig. 2.2.1.

After the fluid drag coefficient $C_D$ is calculated, the settling velocity for a spherical particle can then be predicted by the following equation:
Since the viscosity of a Newtonian fluid is a constant and it does not change with the shear rate imposed on the fluid around the particles, particle settling velocity in a dynamic Newtonian fluid should be the same as that in static ones, which was confirmed by experimental data\(^{(78)}\).

\[
v_\text{s} = \left( \frac{4}{3} \cdot g \cdot \frac{(\rho_s - \rho_f) \cdot d}{C_D \cdot \rho_f} \right)^{1/2}
\]

(2.2.7)

Fig. 2.2.1 Relationship between drag coefficient and particle Reynolds number for particle settling in Newtonian fluids.

2.2.2 Cuttings settling in static non-Newtonian drilling fluids

For the design of the fluid carrying capacity in vertical wells, cuttings settling velocity is required. Even up to now\(^{(72,73)}\), the settling velocity has been calculated by settling velocity models established using particle settling velocity data collected in static drilling fluids. Several experimental measurements of cuttings settling velocity in quiescent non-Newtonian fluids have been conducted\(^{(3,6,8,18)}\). Using their experimental data as a basis, several cuttings settling velocity models have been developed, which are shown in Table 2.2.1. These models have been used to calculate cuttings settling velocity in dynamic drilling fluids for the design and analysis of fluid carrying capacity in vertical wells. However, since drilled cuttings transport happens in an annulus while the drilling fluid is in...
Table 2.2.1 Cuttings settling velocity models derived by various researchers

<table>
<thead>
<tr>
<th>Authors</th>
<th>Flow Regime</th>
<th>Cuttings Shape and Orientation</th>
<th>Settling Velocity Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pigott (1941)</td>
<td>Laminar</td>
<td>Spheres</td>
<td>$v_s = \frac{g \cdot (\rho_s - \rho_f) \cdot d_s^2}{18 \mu}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disk</td>
<td>$v_s = \frac{g \cdot (\rho_s - \rho_f) \cdot d_s^2}{46.3 \mu}$</td>
</tr>
<tr>
<td></td>
<td>Turbulent</td>
<td>Spheres</td>
<td>$v_s = 1.58 \left(\frac{g \cdot (\rho_s - \rho_f) \cdot d_s}{\rho_f}\right)^{1/2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disk</td>
<td>$v_s = 0.61 \left(\frac{g \cdot (\rho_s - \rho_f) \cdot d_{sd}}{\rho_f}\right)^{1/2}$</td>
</tr>
<tr>
<td>Hall, et al. (1950)</td>
<td>Laminar</td>
<td>Spheres</td>
<td>$v_s = \frac{d_s^2 \cdot (\rho_s - \rho_f) \cdot g - 6 d_s \cdot \tau_y}{18 \mu_{eq}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disks</td>
<td>$v_s = \frac{3 \pi h_s d_{sd} (\rho_s - \rho_f) g - 6 \pi \tau_y (d_{sd} + 2 h_s)}{64 \mu_{eq}}$</td>
</tr>
<tr>
<td></td>
<td>Turbulent</td>
<td>Spheres and Disks</td>
<td>$v_s = \frac{\mu_{eq} \cdot N_{Res}}{\rho_f \cdot d_{sv}}$, $N_{Res} = f(C_D \cdot N_{Res}^2)$</td>
</tr>
<tr>
<td>Williams and Bruce (1951)</td>
<td>Turbulent</td>
<td>Spheres</td>
<td>$v_s = \frac{1.74 \left(\frac{g \cdot (\rho_s - \rho_f) \cdot d_s}{\rho_f}\right)^{1/2}}{1 + \frac{d_s}{d}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disk Flatwise</td>
<td>$v_s = 1.35 \left(\frac{g \cdot (\rho_s - \rho_f) \cdot h_s}{\rho_f}\right)^{1/2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disk Edgewise</td>
<td>$v_s = 1.80 \left(\frac{g \cdot (\rho_s - \rho_f) \cdot h_s}{\rho_f}\right)^{1/2}$</td>
</tr>
<tr>
<td>Chien (1970)</td>
<td>Turbulent</td>
<td></td>
<td>$v_s = \left(\frac{4 g (\rho_s - \rho_f) \cdot d_s}{3 \cdot 1.72 \rho_f}\right)^{1/2}$</td>
</tr>
<tr>
<td>Zeidler (1972)</td>
<td>Laminar</td>
<td>con. = 0.049, m = 0.782</td>
<td>$v_s = \text{con.} \left(\frac{4 g}{3}\right)^{m} \cdot \rho_f^{m-1} \cdot (\rho_s - \rho_f)^m \cdot d_s^{3m-1}$</td>
</tr>
<tr>
<td></td>
<td>Transition</td>
<td>con. = 0.172, m = 0.612</td>
<td>$v_s = \text{con.} \left(\frac{4 g}{3}\right)^{m} \cdot \rho_f^{m-1} \cdot (\rho_s - \rho_f)^m \cdot d_s^{3m-1}$</td>
</tr>
<tr>
<td></td>
<td>Turbulent</td>
<td>con. = 0.441, m = 0.516</td>
<td>$v_s = \text{con.} \left(\frac{4 g}{3}\right)^{m} \cdot \rho_f^{m-1} \cdot (\rho_s - \rho_f)^m \cdot d_s^{3m-1}$</td>
</tr>
</tbody>
</table>
Table 2.2.1 (Cont.) Cuttings settling velocity models derived by various researchers

<table>
<thead>
<tr>
<th>Authors</th>
<th>Flow Regime</th>
<th>Cuttings Shape and Orientation</th>
<th>Settling Velocity Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moore (1974)</td>
<td>Laminar</td>
<td></td>
<td>[ v_s = \frac{g \cdot (\rho_f - \rho_f) \cdot d_s^2}{30 \mu_{eq}} ]</td>
</tr>
<tr>
<td></td>
<td>Transition</td>
<td></td>
<td>[ v_s = 0.154 \frac{d_s^2 [g (\rho_s - \rho_f)]^{2/3}}{(\rho_f \cdot \mu_{eq})^{1/3}} ]</td>
</tr>
<tr>
<td></td>
<td>Turbulent</td>
<td></td>
<td>[ v_s = \left[ \frac{4}{3} \frac{g (\rho_s - \rho_f) \cdot d_s}{1.5 \rho_f} \right]^{1/2} ]</td>
</tr>
<tr>
<td>Walker and Mayes (1975)</td>
<td>Laminar</td>
<td>Disks</td>
<td>[ v_s = 41.8 \left[ \frac{h_s (\rho_s - \rho_f)}{\rho_f} \right]^{1/2} ] and ( \tau_s = 68.59 \cdot [h_s (2.49 - \rho_f)]^{1/2} )</td>
</tr>
<tr>
<td></td>
<td>Turbulent</td>
<td></td>
<td>[ v_s = 0.048 \tau_s \left[ \frac{d_s}{\rho_f^{1/2}} \right]^{1/2} ]</td>
</tr>
<tr>
<td>Pedden and Luo 1987 (18)</td>
<td>Laminar</td>
<td>( a=39.8-9n ), ( b=1.2-0.47n )</td>
<td>[ v_s = \frac{3}{4} \frac{0.03 d_s^{(l+bn)}}{a F_{s}^{b} \rho_f^{(1-b)} (10^3)^{-b}} \left[ (10^{-3} F_s)^{(l+bn)} \right]^{1/2} ]</td>
</tr>
<tr>
<td></td>
<td>Transition</td>
<td>( a=42.9-23.9n ), ( b=1-0.33n )</td>
<td>( F_s = 1.5 - 0.54(N_{Rep} &lt; 1) )</td>
</tr>
<tr>
<td></td>
<td>Turbulent</td>
<td>( a=0.35 ), ( b=0 )</td>
<td>( F_s = 2.6 - 1.64(N_{Rep} &gt; 1) )</td>
</tr>
</tbody>
</table>
motion, particle settling in a static fluid can't reveal the actual transport process of the cuttings due to the following reason:

- Drilling fluids are usually shear thinning non-Newtonian fluids. The fluid viscosity is decreasing as the shear rate imposed on the fluid is increased. For a flowing fluid, its viscosity will be different from that in static fluids because of the additional shear imposed by the fluid motion. Thus cuttings settling velocity in a static drilling fluid may be quite different from that in a flowing fluid.

Therefore, a lot of studies have been carried out for cuttings settling velocity at dynamic flow conditions, which are discussed in the following section.

### 2.2.3 Critical review of the previous studies of cuttings settling in dynamic non-Newtonian drilling fluids

Though a lot of experiments have been conducted for cuttings settling velocity under static non-Newtonian drilling fluids, these data can't be used for cuttings transport design with confidence. However, because of the complexities of the measurements, in the opinion of the present author, no valid experimental data are available for particle settling in dynamic drilling fluids. As a matter of fact, the measurements of cuttings settling velocity in dynamic drilling fluids are complicated due to the following reasons:

- There is a changing fluid velocity profile in the annulus.
- Drilled cuttings are transported upward with a changing trajectory due to the complicated annular flow characteristics and this makes it extremely difficult to trace the cuttings and measure their settling velocities accordingly.
- The positions of the cuttings inside the drilling annulus are extremely difficult to measure even if the cuttings are transported along unchanged radial positions.

Therefore, particle settling velocities in dynamic drilling fluids can only be obtained by taking the following measurements simultaneously:

- The particle transport velocities;
- The fluid velocities surrounding the settling particles.
Thus, at least the following measurements need to be made for cuttings settling at actual flow conditions:

- Cuttings transport velocity;
- The exact locations of the cuttings in the annulus;
- The fluid velocity profile across the annulus.

Otherwise, dynamic cuttings settling velocity data can not be obtained. In this section, a brief overview is presented for the various experimental methods of measuring cuttings settling velocity in actual flow conditions.

a. Cuttings transport ratio method

Sifferman et al\(^{(7)}\) used the cuttings transport ratio to indirectly deduce the cuttings settling velocity at dynamic flow conditions. The procedure is that by injecting cuttings into the bottom of a specially designed simulator at a constant rate, the cuttings concentration in the annulus was measured at equilibrium conditions, at which the injection rate is equal to the recovery rate at the top of the simulator. Then the concept of cuttings transport ratio, which is the ratio of cuttings transport velocity to the average annular fluid velocity and which is also the ratio of cuttings injection rate to the cuttings concentration in the annulus, was used to deduce the cuttings settling velocity:

\[
F_T = \frac{v_t}{V_f} = \frac{c_{inj}}{c_{ann}}
\]  

(2.2.8)

In Eq. 2.2.8, the injection concentration of the cuttings \(c_{inj}\), the average fluid velocity \(V_f\) can be directly known based on the experimental parameters. The cuttings concentration in the annulus \(c_{ann}\) at equilibrium condition was measured using a radiation meter. Therefore, the “average” cuttings transport velocity \(v_t\) can be easily obtained. Thereafter the cuttings settling velocity can be calculated using \(v_s = v_f - v_t\) from Eq. 2.1.1.

The advantage of the method by Sifferman et al is that the cuttings concentration inside the annulus was used as the experimental parameter, which is regarded as a very important indicator for vertical hole cleaning efficiency. This technique has been able to avoid the exit and entrance effects of the fluid. However, the following arguments may be raised:
• The fluid has a velocity profile in the annulus. This causes the cuttings being transported at different velocities even if the cuttings settling velocity is the same across the annulus.

• Because of the shear rate profile in the annular flow, cuttings settling velocity is different from position to position in the annulus due to the different shear rates imposed on the fluid by fluid motion. This, combined with the fluid velocity profile in the annulus, makes the cuttings net transport velocities vary widely.

Because of the above reasons, Sifferman et al(7) concluded that cuttings settling velocity data covered a wide trend band and are very scattered, especially in high viscous laminar fluid flow. They could not explain their observations. In fact, these conclusions are very easy to understand while taking the fluid velocity profile into consideration.

b. **Time and distance measurements**

Hall et al(2) measured the average cuttings settling velocity under actual flow conditions. The experimental procedure is as follows: First of all, inject some cuttings into the bottom of the annulus. Then the fluid is circulated at a given flow rate and the cuttings are collected at the top section of the simulator. The time of their arrivals to the surface is recorded correspondingly. Thereafter, the average transport velocity was calculated and so was the average cuttings settling velocity. The arguments against this method can be summarised as follows:

• The exit and entrance effects could not be avoided because the cuttings need to be transported all the way through and up to the exit at the top of the simulator.

• This method again has failed to use the fluid flow field and obviously scattered experimental data are inevitable. The cuttings are transported at much higher velocities in the central region than that in the region close to the wall. The cuttings at the central region of the annulus may be transported at a higher velocity than the average fluid velocity. This can be reflected by the “negative” cuttings settling velocities observed. The so called negative settling velocity is that the
cuttings transport velocity is higher than the average fluid velocity, which has been shown in Fig. 2.2.2.

![Graph showing the predicted cuttings settling velocity versus the experimental data in laminar flow regime by Hall et al.](image)

**Fig. 2.2.2** The predicted cuttings settling velocity versus the experimental data in laminar flow regime by Hall et al.

Similar results for the "negative" cuttings settling velocity as reported by Hall et al. (2) have also been observed by Williams and Bruce (3). It was reported that on the basis of settling velocity equations, the cuttings transport velocities for the first particles returned from the wellbore are higher than the average annular fluid velocity when high-viscosity, high-gel muds are used. This has also reflected the fact that there is a cuttings transport velocity profile in the annulus due to the combination of fluid velocity profile and cuttings settling velocity profile, which is supported by the present new model as presented in chapter 7.

Williams and Bruce (3) and Zeilder (6) have never recovered 100% of the injected cuttings during their experiments. It was deduced that particles appear to adhere to the annular walls. In fact this may be simply due to the fact that the fluid velocity is not high enough to
remove all the cuttings or the duration of the experiments is not long enough for the cuttings close to the wall to reach to the surface.

From the above analysis, it can be seen that no experiments have taken the following necessary measurements for cuttings settling velocity in dynamic fluids as discussed previously:

- Cuttings transport velocity;
- The exact location of the cuttings in the annulus;
- The fluid velocity profile across the annulus.

Thus, the experimental data for cuttings settling velocity at dynamic flow conditions would be in error.

2.3 Concepts to define fluid carrying capacity in vertical wells

Fluid carrying capacity is the ability of the drilling fluid to transport the drilled cuttings up to the surface. Several different concepts have been used to define vertical hole cleaning efficiency, which are discussed in this section.

2.3.1 Cuttings settling velocity

Since cuttings settling velocity was introduced into the study on drilled cuttings transport by Piggot(1), it has always been used by drilling engineers to evaluate vertical hole cleaning efficiency. Obviously, the higher the cuttings settling velocity, the lower the fluid carrying capacity. Whenever hole cleaning needs to be improved, the basic philosophy is to adjust the fluid viscosity so as to reduce the cuttings settling velocity. Unfortunately, up to now, no reliable models and experimental data are available for cuttings settling in dynamic non-Newtonian drilling fluids. It should be pointed out that cuttings settling velocity alone can not reflect cuttings transport process. Hole cleaning needs to be analysed by cuttings transport across the entire annular space.
2.3.2 Annular cuttings concentration

Piggott\(^1\) reported in his classic paper that 5\% of cuttings by volume in the annulus was likely to cause hole problems, which was supported by Hopkin\(^4\). The 5\% maximum cuttings concentration for avoiding vertical hole cleaning problems has been in fact used ever since by drilling engineers. Clearly, cuttings concentration in the annulus is a good indicator for hole cleaning. The higher the cuttings concentration in the annulus, the worse the cuttings transport efficiency. However, the difficulty is how to accurately predict the cuttings concentration in practice.

2.3.3 Cuttings transport ratio

Cuttings transport ratio was defined by Sifferman et al\(^7\) in 1974. It is taken as the ratio of the cuttings net moving velocity to the average annular fluid velocity as shown in Eq. 2.1.2. It was also regarded as the ratio of cuttings feed concentration to the cuttings concentration in the annulus. This concept is superior to cuttings settling velocity, for it gives clearer idea how quickly drilled cuttings are transported up to the surface and how much cuttings are accumulated in the annulus. However, cuttings transport ratio has the following limitations:

- Cuttings transport ratio can be only used in vertical wells.
- This concept has only reflected the overall cuttings transport process. It is only a rough average of the cuttings movement.

2.3.4 Circulation time versus cuttings recovery rate

Williams and Bruce\(^3\) investigated cuttings transport efficiency using both a laboratory simulator and a field rig. The experimental procedures are:

- A certain amount of cuttings was inserted into the bottom of the simulator or rig.
- Then the cuttings were circulated out of the borehole at a given flow rate.
- The cumulative percentage of the number of cuttings recovered against the time was plotted.
It was reasoned that the steeper the slope of this curve, the higher the fluid carrying capacity. According to their study, low viscosity fluid in turbulent flow would give a better transport than high viscosity fluid in laminar flow. Therefore, it was generalised that low viscosity fluid in turbulent flow was advantageous compared to high viscosity fluid in laminar flow regime.

Zeidler (6) also conducted removal rate measurement of drilled cuttings in a full scale simulator. It was also concluded that turbulent flow gave a better cuttings transport. However, Zeidler claimed that the concept of relative velocity \((V_f-V_s)\) does not adequately predict the removal and transport of particles in laminar flow. The maximum cumulative fraction recovered for any one particular particle size was less than one. Large differences have been observed between the experimental data and the model predictions. The settling velocity equations can not be used with any expectation of good results if the fluid is highly viscous and has high gel strength.

About the concept of cuttings recovery rate, the author would like to make the following comments:

- This concept could not predict the cuttings transport velocities in the annulus. It only reflects the fact that as long as the cuttings have roughly the same transport velocity, the slope of the curve produced will be steeper. This will give a higher hole cleaning efficiency, even when cuttings transport velocity is much lower than in some other fluids. This is obviously misleading because what we expected is that the cuttings can be transported smoothly out of the hole during drilling operations rather than the cuttings must be transported up to the surface at roughly the same velocities.

- This method has no reflection of the overall cuttings accumulation in the annulus during drilling operations. A well accepted fact is that increasing fluid viscosity will reduce the cuttings settling velocity. This obviously reduces the cuttings accumulation there. However, because of the fluid velocity profile for laminar flow regime, the cuttings transport velocity may vary in a wider range than the cuttings transport velocity in turbulent flow. This may simply mean that the slope
of the cuttings recovery rate against time is less steep in laminar flow regime than that for turbulent flow regime, which leads to the conclusion that turbulent flow provides better transport.

Zeidler reported that for all the tests, no one has recovered 100% of the injected cuttings. This may be due to the fact that the point velocities in some parts of the annulus are less than the particle settling velocity so that these cuttings could not be recovered.

2.4 Drilled cuttings transport in deviated wells

The papers we have discussed so far are only about drilled cuttings transport in vertical wells. The investigation into cuttings transport in inclined annuli was started in the 1970s when Iyoho(19) reported the first comprehensive study of its kind. Based on the same experimental data, another paper was published by Tomren et al.(20) in 1983. An experimental rig was built to investigate cuttings transport process, by which all the drilling parameters, except for the drill pipe orbital motion, can be simulated. Their major experimental observations and conclusions derived are:

- 0° to 10° from the vertical were defined as low hole angles. Angles of 10° to 30° were named as the intermediate hole angles. 30° to 50° were defined as "transition" or "critical" hole angles, for not only a cuttings bed was formed but also the bed may slide downward along the low side wall of the annulus. At high hole angles of 60° to 90° a cuttings bed was formed very quickly. The particular phenomenon observed was that cuttings above the bed may consist of two zones. The first zone was a narrow layer saltating and sliding axially just above the bed: and the other zone just above this narrow layer was travelling smoothly.

- Drill pipe eccentricity, which was defined in Fig. 2.4.1, had no effect on cuttings transport in vertical wells. For inclined wells concentric annuli gave the best hole cleaning. Turbulent flow provided better cuttings transport in deviated wellbores.

- It was concluded that "cutting transport ratio" was only valid for vertical wells. The concept of "General Transport Ratio" was introduced to define cuttings transport in deviated wells.
The major factors affecting cuttings transport in inclined wells are fluid velocity, hole inclination, and drilling parameters such as mud weight and hole geometry on cuttings injection. The cuttings injection concentration, fluid density, and hole profile and fluid velocity profile and cuttings transport significantly affect cuttings transport. Moderate effects are due to cuttings injection concentration, fluid density, hole profile, and fluid velocity profile and cuttings transport.

In 1986, Kuroda and Sato(13) summarized the results of many studies on shallow depth drilled in the South China Sea. It was concluded that drilling the formation with vertical and low-angle holes, the wells can be drilled more efficiently with less equipment. Also, the fluid yield point in turbid water can be used to provide effective hole cleaning.

Fig. 2.4.1 Definition of drillpipe eccentricity by Iyohno(19)
transport efficiency in deviated wells, which took the cuttings bed into consideration.

- The major factors affecting cuttings transport in inclined wells are fluid velocity, hole inclination and mud rheological properties; moderate effects are due to cuttings injection rate, pipe/hole eccentricity, flow regime, velocity profile and inner pipe rotation; and minor effect from cuttings size distribution.

In 1985, Becker and Azar\(^{21}\) presented the effects of mud weight and hole-geometry on cuttings transport in deviated wells. The same apparatus and test procedures by Iyoho\(^{19}\) were used during the experiments. The volumetric cuttings concentration in the annulus was also used to evaluate cuttings transport efficiency. A detailed analysis of the mechanisms of cuttings transport in inclined wells was described. The bed formation and cuttings deposition in an inclined annulus were fully defined. It was concluded that:

- Reducing the annular cross-sectional area increased cuttings concentration in the annulus and thus decreased hole cleaning efficiency. However, if the annular gap was large enough, drill pipe size only had a minimal effect on cuttings transport.
- An increase in mud weight can improve cuttings transport. Drill pipe rotation had little effect on hole cleaning efficiency.
- The centralisers used to support the inner tube at a desired location in the annular cross-section had a negligible effect on cuttings transport process.

In 1986, Kairon and Schroeter\(^{22}\) summarised the wells of high angle, shallow depth drilled in the South China Sea. It was claimed that by controlling the penetration rate below 90 m/hr., the wells can be drilled most efficiently. It was concluded that turbulent flow with drill pipe rotation provides the best cuttings transport. In actual drilling operations, low mud yield point in turbulent flow regime was used to provide effective hole cleaning.

Also in 1986, Okrajni and Azar\(^{23}\) performed the most extensive investigation into the effects of mud rheologies on cuttings transport in directional wells, including the fluid yield point and yield-point/plastic-viscosity (YP/PV) ratio. It was believed that mud yield value
was the major factor affecting cuttings transport in laminar flow regime. The following conclusions were derived:

- Mud yield value and YP/PV ratio have no effect on cuttings transport in turbulent flow. However increasing mud yield value and YP/PV ratio would increase fluid carrying capacity at low hole angles if the fluid is in laminar flow, which is less pronounced in high angle wells.
- At low hole angles of 0° to 45°, laminar flow is preferred and at high hole angles of 55° to 90°, turbulent flow is preferred. For the medium hole angles of 45° to 55°, either laminar or turbulent flow can provide good hole cleaning.
- Bed sliding down happened at 40° to 45° and the worst transport was observed at this range of hole angles.
- Drill pipe eccentricity has little effect at low angles. But this effect became moderate at high angles in turbulent flow and significant in laminar flow.
- Drill pipe rotation improves cuttings transport, especially at high angle of inclinations.

In the same year, Gavignet and Sobey(24) developed a theoretical model for cuttings transport in highly deviated wells. By considering that two layer transport mechanism is dominant for cuttings removal, a new model for cuttings transport was developed along the lines of Wilson’s(37) model. Because this model neglected the saltation and only considered the fluid viscous forces, it predicted a thicker cuttings bed. The model predictions were compared with the experimental data by Iyoho(19) and a good agreement was reported. As indicated by Iyoho(19), it was also concluded that there is a critical flow rate above which a cuttings bed will not form. Based on their model predictions, the critical flow rate always occurs in turbulent flow regime, which means that turbulent flow gives better hole cleaning. As larger drill pipe provided better cuttings transport, it was recommended that highly deviated wells should always be drilled with as large a drill pipe as possible. It was also concluded that drill pipe eccentricity, particle size, pipe and hole size have strong effects on this critical velocity. However mud rheology, penetration rate and hole angle have little effect on the critical velocity as the hole angle is above 60° from the vertical.
A year later, Martin et al. studied cuttings transport in directional wells both in laboratory and in the field. The attempt is to use accessible parameters in practice to develop applicable models for optimising flow rate and drilling fluid rheology. It was concluded that the minimum fluid velocity required for efficient hole cleaning usually reached nearly maximum at 30° to 60° hole angles. Therefore, their model only considered hole angles below 45°. Above 45°, the minimum flow rate will become a constant. Except for the model, the effect of mud thixotropy was investigated for the first time. It was concluded that:

- The most important parameters of mud rheology were the thixotropy and the effective viscosity. Thixotropy gave a poor cuttings transport in inclined annuli, especially in the case of no inner pipe rotation. If the inner pipe does not rotate, thixotropy causes a practically immobile fluid layer to form near the wall, which may result in poor cuttings transport. The smaller the cuttings, the greater the influence will be. However, inner pipe rotation, when the rotary speed reaches the value to prevent the formation of an immobile layer near the wall, will have a significant effect on cuttings transport. If the fluid is not thixotropic, inner pipe rotation has little effect in turbulent flow and has appreciable effect at low flow rate, especially at 30° to 90° hole angles.
- An increase in fluid density would improve cuttings transport.

The present author would like to point out that thixotropy in fact involves hysteresis effect and time dependent gelation. It's difficult to see how this phenomenon can be isolated and evaluated as suggested above. Maybe the "thixotropy" is really shear thinning in this case.

In 1988, two new models for efficient deviated hole cleaning were developed by Luo. After analysing the extensive studies on both hydraulic transport through pipes and sediment transport in open channels, the initiations of the cuttings movement in a deviated annulus were fully defined. Based on the principle that in order to clean a hole, all the cuttings should be moving upward, two criteria were defined for the cuttings movement. One is the initiation of cuttings moving bed, i.e. a cuttings bed is formed on the low side wall of the annulus, but the cuttings bed is transported upward. The other is the initiation of
cuttings suspension. In this case all the cuttings can be suspended within the drilling fluid and no cuttings bed will be formed i.e. all the cuttings can be transported with the drilling fluid. Based on dimensional analysis, two models were derived and were experimentally established using experimental data\(^{(72)}\).

During the course of the present study, a series of papers were also published, which are also reviewed. In 1989, Brown et al.\(^{(27)}\) reported their experimental and theoretical studies. By using a full scale experimental rig, hole cleaning efficiency at various simulated conditions was evaluated by two methods. One is the annular fluid velocity required to initiate cleaning of the hole. The other is hole cleaning rate. Following the same procedure as that by Gavignet and Sobey\(^{(24)}\), a new model was developed to predict the annular fluid velocity required to clean deviated holes. However a poor correlation was obtained between the experimental data and the theoretical predictions. Based on their studies, the following conclusions were made:

- Deviated hole was more difficult to clean than vertical wells.
- At high hole angles, water in turbulent flow provided the best cuttings transport. However at low hole angles, viscous fluids were more effective for hole cleaning.
- The most difficult hole angles to clean were \(50^\circ\) to \(60^\circ\) from the vertical.

In 1990 Sifferman and Becker\(^{(28)}\) presented a four-year experimental study carried out using a full-scale simulator. Ten parameters were investigated including annular fluid velocity, mud density, fluid rheology etc. Hole cleaning efficiency was defined by the average cuttings-bed height and maximum cuttings-bed height taken as the percentage of wellbore diameter, which was calculated by measuring the arc of angle subtended by the bed at the borehole wall. After the extensive experimental programme, it was concluded that:

- The most important parameters affecting deviated hole cleaning were annular fluid velocity, mud density, hole angle, and drill pipe axial rotary speed.
- Hole cleaning can be substantially improved by a small increase in mud density.
• Drill pipe rotation may improve hole cleaning at near horizontal hole angles, for small cuttings, and at low cuttings concentrations.

• Mud type (oil or water based) had little effect as long as their rheological properties were the same.

• At 45° to 60° hole angles, cuttings bed may continuously slide and tumble downward. Above 60°, the cuttings bed would not slide down even when the circulation was stopped.

Chin published two papers(29, 30) in 1990. In the first paper(29) Chin correlated cuttings concentrations versus the various parameters calculated by his new annular flow modelling, which includes the fluid shear stress, effective viscosity etc. It was claimed that for a fixed hole angle and flow rate, cuttings concentration correlates linearly with the average viscous shear stress over the lower half of the annulus. It was concluded that:

• Yield-point and plastic viscosity, arising from Bingham plastic models, play no direct role in the correlation of hole cleaning efficiency in deviated wells.

• The power law “n” & “K” values are sufficient to characterise the rheological properties of actual drilling fluids.

In the second paper(30) Chin explained by his annular flow modelling why Conoco has successfully drilled several deviated wells using a new all-oil mud. Based on his annular flow analysis, the all-oil mud gave better hole cleaning because of the increased viscous shear stress acting on the cuttings at the low-side wall of the annulus than that invert emulsion fluid.

Also in 1990 Hemphill(31) conducted cuttings transport experiments using oil base drilling fluids. The same experimental rig as Iyoho(19) was used. From the experimental data, the following conclusions were derived:

• Fluid type had little effect on deviated hole cleaning.

• The 100 rpm reading of the Fann VG viscometer is the most significant value of the fluid rheological properties affecting cuttings transport efficiency.
• Hole angle had dominant effect on cuttings transport. There was not much
difference in cleaning 65° and 85° hole angles. However, hole cleaning at higher
hole angles was much worse than that at 45°.

• At high hole angles, the fluids with lower 100 rpm readings can clean the hole
better. At 45° increasing yield point may reduce hole cleaning efficiency.

• Axial pipe rotation only has influence on the local fluids. It has little effect on
cuttings transport as a whole.

Fraser(32) claimed in 1990 that the fluid with a high viscosity at low shear rates can give a
better hole cleaning.

In 1991 another paper was presented by Becker et al.(33). After an extensive analysis on the
experimental data, the following conclusions were drawn:

• 6 rpm readings of the Fann VG viscometer had the best correlation with cuttings
transport.

• For low hole angles (<45°), laminar flow provided better cuttings transport. At
high hole angles (>60°), turbulent flow was preferred. However, if the
experimental data can be extrapolated, higher viscosity fluid may allow laminar
flow to outperform turbulent flow even for near horizontal wells.

• In laminar flow, an increase in fluid viscosity will improve cuttings transport,
which was more pronounced at near horizontal hole angles. However, at
turbulent flow regime, fluid rheology had little effect on hole cleaning efficiency.

Recently, a new cuttings transport model for high-angle wellbores from 55° to 90° from
the vertical was reported by Larsen et al(85). This new model can predict the critical
transport fluid velocity (CTFV) which was defined as the minimum fluid velocity required
to keep all cuttings moving upward. This model can also be used to predict the average
cuttings travel velocity (CTV) and the annular cuttings concentration under any given set of
drilling operating conditions.
It needs to be highlighted that many authors have stressed the effectiveness of turbulent flow on deviated hole cleaning. However, in practice, it would be difficult to achieve turbulent flow in large hole sections. It is impossible for many cases.

2.5 Modelling of drilled cuttings transport

2.5.1 For vertical wells

Modelling of vertical hole cleaning was concentrated on the study of cutting settling velocity and it has been covered extensively in the literature. Some of the models for cuttings settling velocity have been summarised in Table. 2.2.1.

2.5.2 For deviated wells

In this section, the various models developed for the predictions of deviated hole cleaning efficiency are analysed.

a. Gavignet and Sobey's model

Gavignet and Sobey made the first attempt to correlate deviated hole cleaning efficiency. Based on the two layer model by Wilson for hydraulic transport, and considering that a cuttings bed has been formed on the low side annular wall, the overall momentum balance was derived as:

\[ A_c \cdot \tau_c \cdot S_f + A_a \cdot \tau_i \cdot S_i = A_f \cdot \tau_f \cdot S_i \]  (2.5.1)

where \( A_a, A_f \) and \( A_c \) represent the cross-section area of the total annulus, the fluid flow section and the cuttings bed section, respectively; \( S_f, S_c \) and \( S_i \) represent the perimeters of the fluid flow section, the cuttings bed section and the interfacial surface, respectively; \( \tau_f, \tau_c \) and \( \tau_i \) represent the wall shear stresses of the fluid flow section, the cuttings bed section and the interfacial surface, respectively.

The wall shear stress in the fluid flow above the cuttings bed was defined by:

\[ \tau_f = \frac{1}{2} f_f \rho_f v_f^2 \]  (2.5.2)

where \( f_f \) is the fluid friction factor which may be calculated by:
for laminar flow regime, and by:

\[ f_i = \frac{16}{N_{Re}} \]

(2.5.3)

for turbulent flow regime.

The cuttings wall shear stress was calculated by:

\[ \tau_c = \frac{1}{2} f_i \cdot \rho_c \cdot v_c^2 + f_i \cdot (\rho_r - \rho_f) \cdot g \cdot C_s \cdot \sin(\phi) \]

(2.5.5)

The interfacial shear stress was assumed as:

\[ \tau_i = \frac{1}{2} f_i \cdot \rho_r \cdot (v_r - v_c) \cdot |v_r - v_c| \]

(2.5.6)

where \( f_i \) is the interfacial friction factor which was expressed as:

\[ f_i = \frac{2}{\left[4.06 \cdot \log(d_{eq}/d_c) + 3.36\right]^2} \]

(2.5.7)

Gavignet and Sobey's model gave some insights into the cuttings transport process in deviated wells. However, the various assumptions and simplifications may be unrealistic, which include:

- In the calculations of the wall shear stress, the friction factor has been computed using the correlations for Newtonian pipe flow, Eqs. 2.5.3 and 2.5.4.
- The cuttings wall shear stress and interfacial shear stress have been assumed to be Eq. 2.5.5 and Eq. 2.5.6 respectively.
- How to calculate the velocity of cuttings layer \( v_c \) was not explained.

It was noticed that a similar model was developed by Brown et al.\(^{(27)}\). But a quite poor correlation between the experimental data and theoretical predictions was reported. This further demonstrated that the above model can not adequately predict cuttings transport process in deviated wells.

b. **Martin et al model\(^{(25)}\)**

Martin et al. presented a model for deviated hole cleaning, which can be used to calculate the recovery rate of cuttings at the surface versus time. It was expressed as:
where $c$ is a function of hole angle and fluid velocity, which has been established based on their experimental data and was incorporated into a computer programme:

$$c = f(\phi, \mu)$$  \hspace{1cm} (2.5.9)

Concerning the above model, the following arguments may be raised:

- $v_{mt}$ was not clearly defined. It was claimed that this velocity was to determine the cuttings recovery rate at given drilling conditions. The present author can not see any physical meaning if one considers that at equilibrium conditions, the cuttings recovery rate should be equal to the cuttings injection rate.

- For actual drilling fluids the effective viscosity is shear dependent and its value varies in a wide range. How to choose the fluid viscosity was not explained.

- Both cuttings size and annular geometry were not included in the model, which are very important parameters affecting cuttings transport.

c. **Luo's model** \((25,72)\)

Based on the philosophy that in order to clean all the cuttings up to surface, all particles must be moving forward along the hole wall. According to the analysis of forces acting on the cuttings resting on the low-side annular wall, two kinds of cuttings transport mechanisms have been identified. One is that all the cuttings can be suspended within the transporting fluids and the cuttings are being transported together with the drilling fluid. The other is that the cuttings are being transported as a moving bed. Based on these two transport mechanisms, parameters have been identified for the initiations of cuttings movements in a deviated wellbore.

For cuttings rolling or sliding:

$$f(\rho_r, \mu_c, \rho_s, d_s, b_c, g \cdot (\rho_s - \rho_r) \cdot \cos(\Phi), v_{mt}) = 0$$  \hspace{1cm} (2.5.10)

and for cuttings suspension:
Using dimensional analysis, two MTV models have been derived for the initiations of cuttings transport in deviated wells.

The MTV model for cuttings rolling/sliding is expressed as:

\[
f \left( \rho_f, \mu_c, \rho_c, d_s, b_{ea}, \gamma \cdot (\rho_c - \rho_f) \cdot \sin(\Phi), v_{mt} \right) = 0 \tag{2.5.11}
\]

and the MTV model for cuttings suspension was given as:

\[
\frac{v_{mt}^2}{d_s g \left( \frac{\rho_c - \rho_f}{\rho_f} \right) \left( \cos(\Phi) + f_s \sin(\Phi) \right) \mu_c} = m_s \left( \frac{d_s v_{mt} \rho_f}{\mu_c} \right)^m \left( \frac{d_s}{b_{ea}} \right)^n \tag{2.5.12}
\]

and the MTV model for cuttings suspension was given as:

\[
\frac{v_{mt}^2}{d_s g \left( \frac{\rho_c - \rho_f}{\rho_f} \right) \sin(\Phi) \mu_c} = n_s \left( \frac{d_s v_{mt} \rho_f}{\mu_c} \right)^{a_s} \left( \frac{d_s}{b_{ea}} \right)^{b_s} \tag{2.5.13}
\]

In a later paper(72), Eq. 2.5.13 has been established using experimental data. Though the above two models have used a very good concept to define deviated hole cleaning efficiency, the following points may need to be discussed:

- Dimensional analysis has been directly used for the model development.
- Friction velocity was used for the force analysis. In fact, the fluid velocity around the particles should be used to calculate the force acting on the cuttings resting on the low-side annular wall.

d. Larsen et al's model(85)

Larsen et al(85) reported a new model for the predictions of the critical transport fluid velocity \( v_{crit} \), which is defined as the minimum fluid velocity required to maintain a continuously upward movement of the cuttings. Based on the principle of mass balance on the cuttings,

\[
\text{Mass Generated by Drill bit} = \text{Mass Transported by Mud} \tag{2.5.14}
\]

the average cuttings transport velocity in a deviated annulus was derived as:
Based on their experimental data, the relationship between $C_\alpha$ and ROP corresponding to
the $v_{\text{crit}}$ was found to be:

$$C_\alpha = 0.058333 \cdot \text{ROP} + 0.505 \quad (2.5.16)$$

Replacing Eq. 2.5.16 into Eq. 2.5.15, it was obtained that:

$$v_{\text{cut}} = \frac{1}{\left(1 - \left(\frac{d_1}{d_2}\right)^2\right) \cdot \left(0.021 + \frac{0.1818}{\text{ROP}}\right)} \quad (2.5.17)$$

The authors concluded without reasoning that the critical transport fluid velocity $v_{\text{crit}}$ can be
found by adding the cuttings travel velocity $v_{\text{cut}}$ to the generalised slip velocity $v_{\text{slip}}$:

$$v_{\text{crit}} = v_{\text{cut}} + v_{\text{slip}} \quad (2.5.18)$$

By the combination of Eqs. 2.5.17 and 2.5.18, the cuttings slip velocity can be calculated
for each of the experimental data. The fluid effective viscosity can also be calculated by:

$$\mu_e = PV + \frac{YP \cdot (d_2 - d_1)}{7.98 \cdot v_{\text{crit}}} \quad (2.5.19)$$

Thereafter, a plot of $v_{\text{slip}}$ versus the effective viscosity can be obtained. Then, the
correlation between the uncorrected slip velocity and the effective viscosity was obtained
as:

$$\bar{v}_{\text{slip}} = 15.728 \cdot \mu_e + 91.622 \quad (\mu_e < 53 \text{ cp}) \quad (2.5.20)$$

$$\bar{v}_{\text{slip}} = 0.778 \cdot (100 \cdot \mu_e - 53) + 99.97 \quad (\mu_e > 53 \text{ cp}) \quad (2.5.21)$$

By dividing the experimental $v_{\text{crit}}$ mean for the individual angles ($90^\circ$, $75^\circ$, $65^\circ$ and $55^\circ$)
by the average of all angles, the correction factor $C_{\text{ang}}$ against the hole angle has been
derived as:

$$C_{\text{ang}} = 0.0342\Phi - 0.000233\Phi^2 - 0.213 \quad (2.5.22)$$

Correspondingly, by dividing the average $v_{\text{crit}}$ of large, medium and small cuttings by the
individual $v_{\text{crit}}$, the cuttings size correction factor has been obtained as:
Similarly, mud weight correction factor was obtained as:

\[
C_{\text{mwt}} = 1 \pm 0.0333 \cdot (8.34 \cdot \rho_f - 8.7) \quad (\rho_f > 1.044) \\
C_{\text{mwt}} = 1.0 \quad (\rho_f < 1.044)
\] (2.5.24)

The generalised slip velocity of cuttings is then expressed as:

\[
v_{\text{slip}} = \bar{v}_{\text{slip}} C_{\text{ang}} C_{\text{size}} C_{\text{mwt}}
\] (2.5.26)

Finally, the critical transport fluid velocity \( v_{\text{crit}} \) was obtained by adding the cuttings travel velocity to the generalised \( v_{\text{slip}} \) as has been shown in Eq. 2.5.19.

The present author found the following assumptions and expressions are difficult to understand:

- For the correlation of the critical transport fluid velocity \( v_{\text{crit}} \), Eq. 2.5.18 was given without reasoning.
- The present author can not understand the physical meanings of the definitions of the various correction factors used for the calculations of the equivalent slip velocity of the cuttings including Eq. 2.5.26 itself.
- The model can only be used for highly deviated wells from 55° to 90°.

From the discussions, it may be concluded that no reliable models are available for the predictions of deviated hole cleaning efficiency and more theoretical work needs to be carried out for the modelling of deviated hole cleaning efficiency.

2.6 Modelling of annular fluid flow

As one of the most important aspects of cuttings transport studies, modelling of annular fluid flow, especially for eccentric annuli or concentric annuli with pipe rotation, has been carried out by various researchers(26, 39-45).

In 1980 Iyoho(39) presented a theoretical study on eccentric annular flow of Non-Newtonian fluids. Instead of using iterative finite-difference method, an eccentric annulus
was treated as a slot with various heights and a more accurate model was derived for the fluid velocity profile.

In 1987 Peden and Luo\(^{(40)}\) reported a new solution procedure for non-Newtonian fluid flow through eccentric annuli by treating an eccentric annulus as infinite concentric annuli with variable outer radii. Analytical solutions of the shear stress and velocity profiles for both power law and Bingham plastic fluids were obtained.

Chin\(^{(44)}\) approached this problem using a different method. The eccentric annular flow was analysed by finite difference technique, which can take the cuttings bed formation into consideration. All the fluid flow profiles were derived including velocity profile, shear stress & shear rate profiles, fluid effective viscosity profile.

Another theoretical analysis on non-Newtonian fluid flow through eccentric annuli was carried out by Haciislamoglu\(^{(41)}\) in 1989. Taking the work by Guckes\(^{(42)}\) as a guide-line, the partial differential flow equation for Herschel-Bulkley fluids through eccentric annuli was solved using Bipolar co-ordinates. Though Haciislamoglu claimed that Peden & Luo\(^{(40)}\) and Iyoho\(^{(39)}\) used the incorrect flow equation, which gave a two dimension problem a one dimension solution, the study by Haciislamoglu provided no better solution than Guckes\(^{(42)}\), for Haciislamoglu did not define the unsheared plug boundaries, which were the important flow feature of the fluids with a yield stress.

Although different researchers have derived different flow equations for the eccentric annular flow of non-Newtonian fluids, the following characteristics are described which may have some influence on deviated hole cleaning:

- The local fluid velocity in the reduced region of an eccentric annulus was lower than that in the enlarged region.
- The shear stress in the reduced region of an eccentric annulus was lower than that in the enlarged region and so is the shear rate.
- The fluid point velocity varies in a wide range. The average fluid velocity could not represent the overall fluid flow characteristics and neither could the average fluid effective viscosity.
Helical flow of non-Newtonian fluid helical flow through a concentric annulus was investigated by Luo\textsuperscript{(26)}, Lui & Zhai\textsuperscript{(43)}, and Chin\textsuperscript{(45)}. Based on these studies, the following conclusions may be drawn:

- For a Newtonian fluid, its viscosity is constant and thus not shear dependent. The axial and the tangential components of helical flow are independent of each other.
- Pipe rotation will induce some additional shear to the fluid. This will reduce the fluid effective viscosity.
- The axial pressure gradient will be decreased at a constant flow rate or the flow rate will be increased at a constant axial pressure gradient.

2.7 Factors affecting cuttings transport

From the above analysis, it can be known that the factors affecting cuttings transport include:

- Annular fluid velocity
- Hole geometry and annular size (including hole enlargement)
- Hole angle
- Drill pipe eccentricity
- Drill pipe rotary speed including orbital motion
- Drilling fluid rheological properties and density
- Fluid flow regime and particle moving regime
- Cuttings size, density and size distribution
- Rate of penetration (cuttings concentration)

These factors have been analysed by various researchers. As is discussed in section 2.9, some contradictory conclusions exist on how the various parameters may affect drilled cuttings transport. In chapter 5, the effects of the various parameters on deviated hole cleaning are analysed based on the present experimental data. Further more, chapter 9 presents an extensive discussion of the various factors affecting drilled cuttings transport using all the up to date knowledge and information.
It needs to be highlighted that drill pipe orbital motion has dramatic effect on hole cleaning at various hole angles as discussed in chapter 5. However, no experimental data concerning the effect of drill pipe orbital motion were available in the literature. In the present study, some specially designed experiments were carried out to evaluate its effect and its effect on hole cleaning efficiency was also incorporated into the newly developed MTV package for hole cleaning design and analysis.

2.8 Experimental equipment and facilities

All the experimental parameters and facilities used by previous researchers have been compiled in Table 2.8.1. As stated by Iyoho(19), there are two basic requirements for the effective simulation of actual drilling situations:

- The experimental rig must be long enough for the fluid to reach steady flow.
- The apparatus must allow the selection of the various drilling variables to simulate different drilling situations including flow rate, hole angle, drill pipe rotary speed, pipe eccentricity etc.

The first such an experimental rig was built in Tulsa University. Since then, a very extensive experimental programme has been carried out(19,20,21,23,33). The experimental rig has been shown in Fig. 2.8.1. From the figure it can be seen that except for the flexible simulated variables, some other systems have also been built including the data acquisition, video-recording etc. This has made the cuttings transport study more systematic. Although two field-scale experimental rigs have been built later(27 & 28), the basic components are still the same.

2.9 Discussions

Though a lot of efforts have been made for cuttings transport studies, our knowledge is still not sufficient for us to optimise drilling operations in the field. Some of the limitations of the previous investigations are briefly discussed.
<table>
<thead>
<tr>
<th>Investigators</th>
<th>Wellbores</th>
<th>Cuttings</th>
<th>Muds</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pigott (1941)</strong></td>
<td>4&quot; column x 200' 0.5&quot; column x 14.5' 1&quot; column x 176.6'</td>
<td>D = 0.011 - 0.50</td>
<td>Clay mud (Bentonite)</td>
</tr>
<tr>
<td>Field</td>
<td>7&quot; hole x 3.5&quot; pipe 10&quot; hole x 4.5&quot; pipe 18&quot; hole x 4.5&quot; pipe</td>
<td>Round Flat</td>
<td>Bentonite</td>
</tr>
<tr>
<td><strong>Hall Thompson &amp; Nass (1950)</strong></td>
<td>4&quot; column x 33' 1.25&quot; column x 9' (long)</td>
<td>Glass 2.30 2.43</td>
<td>Bentonite</td>
</tr>
<tr>
<td>Lab</td>
<td>9-5/8&quot; Casing x 4-1/2&quot;/drill pipe 1000' deep</td>
<td>Mixture of plastics and Bitumens 2.6</td>
<td>Drilling fluids water</td>
</tr>
<tr>
<td>Field</td>
<td>4&quot; hole x 1&quot; pipe x 5' (long) Opaque plastics</td>
<td>Glass Aluminium Steel Ni-steel Drilled cuttings 2.41-2.60 2.69-2.82 7.77 8.86 8.87</td>
<td>Water</td>
</tr>
<tr>
<td>Lab</td>
<td>7&quot; Casing x 2.5&quot; or 2-7/8&quot; drill pipe 300' deep</td>
<td>Sphere Disc 0.156 - 0.940 0.58 - 0.125 -0.55 - 0.25 0.63 - 0.067</td>
<td>Water</td>
</tr>
<tr>
<td><strong>Williams &amp; Bruce (1951)</strong></td>
<td>Glass Drilled cuttings 8.86 not known</td>
<td>Cuttings</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Field</td>
<td>7-7/8&quot; hole x 4.5&quot; pipe 8-3/4&quot; hole x 4.5&quot; pipe 9&quot; hole x 4.5&quot; pipe</td>
<td>Splice Flat 0.20 - 1.0 0.50 - 0.125 -0.75 - 0.25 0.625 - 0.034</td>
<td>Field mud from Liverpool and Bassett-Blackley</td>
</tr>
<tr>
<td>Field</td>
<td>7-7/8&quot; hole x 4.5&quot; pipe 8-3/4&quot; hole x 4.5&quot; pipe 9&quot; hole x 4.5&quot; pipe</td>
<td>Splice Flat 0.20 - 1.0 0.50 - 0.125 -0.75 - 0.25 0.625 - 0.034</td>
<td>Initial Gel Strength: 0-90 gms-Stommer</td>
</tr>
<tr>
<td><strong>Hopkin (1967)</strong></td>
<td>7-7/8&quot; hole x 4.5&quot; pipe 8-3/4&quot; hole x 4.5&quot; pipe 9&quot; hole x 4.5&quot; pipe</td>
<td>2.5 - 5.8</td>
<td>Analyse on field results</td>
</tr>
<tr>
<td>Investigators</td>
<td>Wellbore</td>
<td>Cuttings</td>
<td>Muds</td>
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<td></td>
<td>Azimuthal Sizes (in)</td>
<td>Hole Angle (deg.)</td>
<td>Eccentricity (%)</td>
</tr>
<tr>
<td>Hopkins (1967)</td>
<td>Lab</td>
<td>4.5&quot; hole x 8&quot; pipe</td>
<td>Glass Sandstone Shale cuttings</td>
</tr>
<tr>
<td>Zeidler (1972)</td>
<td>Lab</td>
<td>3.5&quot; ID glass tube x 15' (long) Four Station Marked</td>
<td>Cartridge marble samples</td>
</tr>
<tr>
<td>Field</td>
<td>8-1/8&quot; ID casing x 4.5 OD pipe x 6' (long)</td>
<td>Cartridge marble samples</td>
<td>ASTM 1/4, 4, 6, 8, 10</td>
</tr>
<tr>
<td>Sijfjesna, Myers, Haden, Wall (1974)</td>
<td>Lab</td>
<td>8&quot; ID casing x 4.5&quot; OD pipe x 6' (long) 12&quot; ID casing x 3.5&quot; or 5&quot; OD pipe 140 high oilfield derick as main frame</td>
<td>Mixture of plastics, wax and lead</td>
</tr>
<tr>
<td>Zeidler (1974)</td>
<td>Lab</td>
<td>3.5&quot; ID x 24&quot; OD pipe x 80 cm (long)</td>
<td>Cartridge marble sample</td>
</tr>
<tr>
<td>Walker Mayers (1975)</td>
<td>Lab</td>
<td>6&quot; ID pipe x 5' long</td>
<td>Various</td>
</tr>
<tr>
<td>Sample Bourgeois (1977)</td>
<td>Lab</td>
<td>1-1/4&quot; ID casing x 1/8&quot; OD pipe x 6' (long)</td>
<td>Mixture of wax, plastics lead, Glass</td>
</tr>
<tr>
<td>Iyino (1980)</td>
<td>Lab</td>
<td>5&quot; ID casing x 1.9&quot; OD pipe x 40' (long)</td>
<td>Actually drilled cuttings</td>
</tr>
<tr>
<td>Investigator</td>
<td>Location</td>
<td>Hole</td>
<td>Annular</td>
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<tr>
<td>Hepkin (1967)</td>
<td>Lab</td>
<td>4.5’ hole &amp; 8” pipe</td>
<td>2.47-</td>
</tr>
<tr>
<td>Zeidler (1972)</td>
<td>Lab</td>
<td>3” glass tube x 15’ (long) Four Station Marked</td>
<td>50-</td>
</tr>
<tr>
<td>Field</td>
<td>8-1/8” ID casing x 4.5 OD pipe x 65’ (long)</td>
<td>57</td>
<td>Cartridge marble samples</td>
</tr>
<tr>
<td>Siffman, Myers, Haden, Wahl (1976)</td>
<td>Lab</td>
<td>8” ID Casing x 4.5” OD pipe 12”ID casing x 3.5” or 5”OD pipe 140’ high oilfield derick as main frame</td>
<td>50-200</td>
</tr>
<tr>
<td>Zeidler (1974)</td>
<td>Lab</td>
<td>12.7 cm ID casing x 2.98 cm OD pipe x 80 cm (long)</td>
<td>0-150</td>
</tr>
<tr>
<td>Walker Mayes (1975)</td>
<td>Lab</td>
<td>6” ID pipe x 5’ long</td>
<td>1.38-</td>
</tr>
<tr>
<td>Sample Bosegope (1977)</td>
<td>Lab</td>
<td>1.34” ID casing x 3.4” OD drill pipe x 6’ (long)</td>
<td>0.10</td>
</tr>
<tr>
<td>Iyoho (1980)</td>
<td>Lab</td>
<td>5” ID casing x 1.5” OD pipe x 40’ (long)</td>
<td>0</td>
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</table>

TABLE 2.8.1 (Cont.-I) Summary of the previous cuttings transport experiments
<table>
<thead>
<tr>
<th>Investigators</th>
<th>Wellbores</th>
<th>Cuttings</th>
<th>Muds</th>
<th>Instruments used</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anular Sizes (in)</td>
<td>Hole Angle (deg)</td>
<td>Eccentricity (%)</td>
<td>Rotary Speed (rpm)</td>
<td></td>
</tr>
<tr>
<td>Thomas Azar Becker (1981)</td>
<td>Lab</td>
<td>5&quot; ID casing x 2&quot; OD drill pipe x 40'</td>
<td>16.7 33.3 50.0 66.7</td>
<td>0 30 50 35</td>
<td>45</td>
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<td></td>
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<td></td>
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<tr>
<td>Hussain Azar (1983)</td>
<td>Lab</td>
<td>5&quot; ID casing x 1.2&quot; OD pipe x 50'</td>
<td></td>
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<tr>
<td></td>
<td>Field</td>
<td>12-1/4&quot; ID casing x 4.5&quot; OD pipe 8.5&quot; ID casing x 4.2&quot; OD pipe 4000-14000' deep hole</td>
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<tr>
<td></td>
<td>Lab</td>
<td>5&quot; ID casing x 1.9&quot; OD pipe x 40'</td>
<td>0, 20, 40, 45, 30, 50, 90</td>
<td>0</td>
<td>+50%</td>
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<tr>
<td></td>
<td>Lab</td>
<td>10-5/8&quot; ID casing x 5&quot; OD pipe x 16' 4-5/8&quot; ID casing x 10'</td>
<td>0.0 90</td>
<td>50-200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lab</td>
<td>8.5&quot; hole x 5&quot; pipe 6&quot; hole x 2-5/8&quot; pipe 5&quot; hole x 3&quot; pipe 8.5&quot; hole x 5&quot; pipe</td>
<td>0 75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investigators</td>
<td>Wellbores</td>
<td>Cuttings</td>
<td>Muds</td>
<td>Instruments used</td>
<td>Remarks</td>
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<tr>
<td>Luo Peden (1987)</td>
<td>3.5&quot; ID casing x 6.5°</td>
<td>Bauxite-propellant</td>
<td>CMC</td>
<td>Computer clock, Stopwatch, Fann VG 33, HAAKE- MV II PVT, Hi-Tm Video camera</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.35&quot; ID casing x 1.48°</td>
<td>Sand, Glass beads</td>
<td>CMC/XC</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Marbles</td>
<td>HEC</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Steel ball</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Aluminum Plastics</td>
<td>Shell Tribol Oil 68</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Brown Born Weaver (1989)</td>
<td>8&quot; ID casing x 5° OD pipe x 5°</td>
<td>Ceramic beads</td>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0, 20, 36, 52, 60, 79 &amp; 90</td>
<td></td>
<td>HEC</td>
<td>50, 100, 150, 200 &amp; 250 ft/min</td>
<td>Full Scale Rig</td>
</tr>
<tr>
<td>Sifferman Becker 1990</td>
<td>8&quot; casing x 3&quot; OD pipe</td>
<td>Sand</td>
<td>Oil muds</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8&quot; casing x 4.5&quot; OD pipe</td>
<td>Various</td>
<td>Water</td>
<td>120-300 ft/min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45, 60, 75 &amp; 90</td>
<td>0</td>
<td>YP=10-30 Bc/lb/gal, Density=9-16 lb/gal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemphill 1990</td>
<td>5&quot; casing x 2.375&quot; pipe</td>
<td>Limestone</td>
<td>Various</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>45, 65, 85</td>
<td>62, 50</td>
<td>20</td>
<td>Densities: 10-10.6 ppg</td>
<td>Up to 340 ft/min</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>PV=16-23 cp</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>YP=8-14 Bc/lb/gal</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2.8.1 (Cont.-III) Summary of the previous cuttings transport experiments**

- **Wellbores**:
  - Annular Sizes (in): 3.5" ID casing, 2.35" ID casing, 8" ID casing, 5" casing.
  - Eccentricity (%): 52, 60, 79 & 90, 0, 100.
- **Cuttings**:
  - Shape: Spheres, Round, Disk, Rectangle.
  - Sizes (in): 0.3-25.1 mm, 1.2-2.2 mm, 6.4 x 2.1 mm, 5.9 x 4.1 x 2.1 mm.
- **Muds**:
  - Type: CMC, CMC/XC, HEC.
  - Properties: Density=0.88-1.015 g/cc, n=0.418-1.00, K=0.0374-3.392 (Pa.s/m).
  - Anular Velocity (ft/sec): 50, 100, 150, 200 & 250 ft/min.
- **Instruments used**: Computer clock, Stopwatch, Fann VG 33, HAAKE- MV II PVT, Hi-Tm Video camera.
- **Remarks**: Full Scale Rig.
a. Schematic side view of experimental rig

b. Schematic top view of experimental facility

Fig. 2.8.1 The experimental rig by Iyoho\(^{19}\) and Tomren et al.\(^{20}\)
2.9.1 How the various drilling parameters may affect cuttings transport

Though drilled cuttings transport has been investigated by many researchers, some confusion still exists on how the drilling parameters may affect fluid carrying capacity. Taking the effects of fluid rheological properties and flow regime as an example, some of the conclusions derived by the different researchers are summarised in Table 2.9.1.

Table 2.9.1 shows that some researchers\(^{(1,4,23,27,32,33)}\) concluded that high viscosity fluids in laminar flow can provide a better hole cleaning than low viscosity fluids in turbulent flow and some other investigators\(^{(2,3,6)}\) observed that low viscosity fluids in turbulent flow regime were more efficient for transporting cuttings. As discussed in sections 5.5.2 and 9.3, the effects of fluid viscosity are very complicated. Depending on the pipe rotary speeds and the level of pipe eccentricity, either low viscosity fluids in turbulent flow or high viscosity fluids in laminar flow may provide efficient cuttings transport. The effects of fluid rheology are strongly pipe rotary speed and pipe eccentricity dependent. However, the previous researchers observed the effects of fluid rheology on hole cleaning efficiency under their own simulated conditions and then the effects were generalised. This proves to be very dangerous. Therefore, some investigations are still required in order to have a better understanding of the transport process.

2.9.2 Models to predict hole cleaning efficiency

From the analysis presented in section 2.5.2, it has been seen that no reliable models are available for the predictions of deviated hole cleaning efficiency. In order to help field engineers to effectively manipulate their drilling parameters, more theoretical modelling is required so that cuttings transport process can be accurately predicted and analysed.
Table 2.9.1 The preferred fluid viscosity and flow regime

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Date</th>
<th>Fluid Viscosity</th>
<th>Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piggot(1)</td>
<td>1941</td>
<td>High</td>
<td>Laminar</td>
</tr>
<tr>
<td>Prokop(2)</td>
<td>1950</td>
<td>Low</td>
<td>Turbulent</td>
</tr>
<tr>
<td>Williams &amp; Bruce(3)</td>
<td>1951</td>
<td>Low</td>
<td>Turbulent</td>
</tr>
<tr>
<td>Hopkin(4)</td>
<td>1967</td>
<td>High</td>
<td>Laminar</td>
</tr>
<tr>
<td>Zeidler(6)</td>
<td>1972</td>
<td>Low</td>
<td>Turbulent</td>
</tr>
<tr>
<td>Okrajni &amp; Azar(23)</td>
<td>1986</td>
<td>High</td>
<td>Laminar</td>
</tr>
<tr>
<td>Brown et al.(27)</td>
<td>1989</td>
<td>High</td>
<td>Laminar</td>
</tr>
<tr>
<td>Fraser(32)</td>
<td>1990</td>
<td>High</td>
<td>Laminar</td>
</tr>
<tr>
<td>Becker et al.(33)</td>
<td>1990</td>
<td>High</td>
<td>Laminar</td>
</tr>
</tbody>
</table>
CHAPTER 3
THE CONCEPT OF MTV FOR HOLE CLEANING AND THE VARIOUS MODELS DESCRIBING DRILLING FLUID RHEOLOGICAL PROPERTIES

The literature review in chapter 2 has shown that many concepts have been used to define fluid carrying capacity of drilled cuttings. In this chapter, a new concept to define adequate cuttings transport is introduced. Then, the cuttings transport mechanisms both in vertical and deviated wells are analysed. Based on the cuttings transport mechanisms, the minimum transport velocity (MTV) required for adequate hole cleaning is defined. The MTV concept for deviated wells are in fact the same as the ones defined by Luo (26). However, the present author has extended the MTV concept into vertical wells. This has made it possible to derive cuttings settling velocity in dynamic drilling fluids, which is presented in chapter 7. Based on the criteria for the initiation of cuttings movement, two MTVs have been identified for deviated hole cleaning. One is the MTV for the initiation of cuttings suspension and the other is the MTV for the initiation of cuttings rolling/sliding forward. In this chapter, the various models describing drilling fluid rheological properties are also discussed.

3.1 Concept of MTV for adequate cuttings transport

In order to clean a hole, all the cuttings need to be transported up to the surface. In actual drilling practice, this should be achieved on a continuous basis so as to avoid excessive accumulation of drilled cuttings in the annulus. In the present study, the criterion for adequate hole cleaning is that all the drilled cuttings are cleaned out of the hole continuously. It is clear that the necessary condition for this is that all the cuttings are moving upward along the hole axis and no cuttings are either stationary or sliding downward in the wellbore. The minimum fluid velocity satisfying the above criterion is
now defined as the MTV required for cuttings transport for both vertical and deviated wells.

3.2 MTV for cuttings transport in vertical wells

Since the cuttings' density is usually higher than that of the drilling fluid, drilled cuttings will settle downward in the drilling fluid under the action of the gravitational force. In vertical wells, in order to continuously transport the drilled cuttings up to the surface, the fluid velocity around the cuttings should be higher than the cuttings settling velocity. Therefore, since Piggott\(^{(1)}\) introduced the concept of cuttings settling velocity to define mud carrying capacity, it has been used by all drilling engineers to design cuttings transport for vertical wells.

If it is assumed that the cuttings are separated so as not to interact with each other, and no electrostatic or other external forces are acting on the cuttings, at equilibrium conditions, there are two forces which are acting on the cuttings in vertical wells as shown in Fig. 3.2.1:

a. The effective gravitational force of the cuttings:

\[
F_g = V_s \cdot (\rho_s - \rho_f) \cdot g
\]  (3.2.1)

b. The fluid drag force which will resist the cutting's settling:

\[
F_D = \frac{1}{2} C_D \rho_f V_s^2 A_p
\]  (2.2.2)

The gravitational force will cause the cuttings settle downward and the fluid drag force will resist cuttings settling. Eq. 2.2.2 shows that as the cuttings settling velocity increases, the drag force acting on the cuttings, which opposes cuttings settling, will be increased. At equilibrium conditions, the cuttings will settle at a constant velocity which is defined as the cuttings settling velocity. Previous researchers\(^{(1-18)}\) have studied cuttings settling velocities in many ways, and different models have been derived for different fluids, particle sizes and shapes.

As discussed in chapter 2, the fluid velocity in the annulus is changing from position to position. Approaching to the borehole/drill pipe wall, the fluid velocity will approach zero.
Therefore, much higher average fluid velocity is required in order to remove the cuttings close to the annular walls. The literature review demonstrated that no valid experimental data are available for cuttings settling velocity in dynamic drilling fluids. The previous researchers have only used cuttings settling velocity in static fluids and the average annular fluid velocity to define vertical hole cleaning efficiency. This obviously can not reveal the cuttings movements across the annulus.

According to the newly defined MTV for hole cleaning, in order to have a adequate cuttings transport, all the cuttings should be transported upwards. Therefore, the fluid velocities across the annulus should be higher than the corresponding settling velocities of the cuttings. The minimum average fluid velocity to satisfy this condition is defined as the MTV for vertical hole cleaning.

3.3 MTV for cuttings transport in deviated wells

In deviated wells, cuttings transport is more complicated than that in vertical wells. Before defining the MTV for deviated hole cleaning, first of all, the cuttings movements in a deviated borehole are analysed. Then the MTV for deviated hole cleaning is defined. The physical force balance models are established for the initiation of movement of the cuttings resting on the low-side annular wall. The MTV models are then defined accordingly.

3.3.1 A cutting travelling in the fluid in a deviated annulus

(1) Forces acting on the cutting

If the same assumptions are made as in the case for vertical boreholes that the cuttings are separated so as not to interact with each other and no electrostatic or other external forces are acting on the cuttings, in deviated wells, the forces acting on the cuttings travelling upward within the drilling fluid are composed of, as shown in Fig. 3.3.1:

a. Cutting's gravitational force

The effective gravitational force $F_g$, which was expressed by Eq. 3.2.1, always forces the cuttings to settle downward. In fact, in inclined boreholes, the gravitational force can be
Fig. 3.2.1 Forces acting on a cutting in a vertical column

Fluid lift force may arise for at least three reasons: 1. The fluid asymmetric velocity around the cuttings such that wherever the cutting is located, a velocity gradient will always exist around the cutting. A pressure difference is set up which results in lifting of the cuttings. 2. The flow is turbulent, an instantaneous fluid velocity normal to the flow direction may exist. The lift force, which is normal to the flow direction, is expressed as:

$$ F_L = C_L \frac{1}{2} \rho v^2 A $$

Fluid drag force.

Fluid drag force may occur if the flow is not parallel to the surface of the force acting on the fluid viscous force. It acts on all surfaces of the cuttings normal to the flow. It may be expressed as:

$$ F_D = C_D \frac{1}{2} \rho v^2 A $$

One is the forces acting normal to the flow direction. The other group is the forces acting parallel to the flow direction. Sometimes it is said that fluid lift force $F_L$ is greater than the fluid drag force $F_D$. Otherwise if the fluid lift force $F_L$ is greater than the fluid drag force $F_D$.

Fig. 3.3.1 Forces acting on a cutting travelling in a deviated wellbore
divided into two components. These two components are $F_{ga}$ which is parallel to the hole axis and $F_{gva}$ which is vertical to the hole axis. They can be respectively expressed as:

$$F_{ga} = F_g \cdot \cos(\Phi) \quad (3.3.1)$$
$$F_{gva} = F_g \cdot \sin(\Phi) \quad (3.3.2)$$

Under the action of the component $F_{ga}$, the cuttings tend to slide towards the hole bottom. $F_{gva}$ makes the cuttings settle towards the low-side annular wall.

b. Fluid lift force

Fluid lift force may arise for at least two reasons. Firstly the fluid asymmetric velocity around the cuttings is such that wherever the cutting is located, a velocity gradient will always exist around the cutting. A pressure difference is set up which results in lifting of the cutting. The second is the instantaneous velocity fluctuations. When the flow is turbulent, an instantaneous fluid velocity normal to the flow direction may exist. The lift force, which is normal to the flow direction, is expressed as(26):

$$F_L = C_L \cdot A_p \cdot \frac{\rho_f \cdot v_p^2}{2} \quad (3.3.3)$$

c. Fluid drag force $F_D$

Fluid drag force which is parallel to the flow direction arises mainly due to the fluid viscous force. It acts on that part of the cutting which is exposed to the fluid flow. It may be expressed as:

$$F_D = C_D \cdot A_p \cdot \frac{\rho_f \cdot v_p^2}{2} \quad (3.3.4)$$

(2) Analysis of the cuttings movement

In deviated drilling annuli, two kinds of forces are acting on a cutting travelling upward. One is the forces acting vertically to the flow direction. The other group is the forces acting parallel to the flow direction.

Fig. 3.3.1 shows that if the fluid lift force $F_L$ is not large enough, the cuttings will settle toward the low-side annular wall. Otherwise if the fluid lift force $F_L$ is greater than the
gravity component force $F_{g_{va}}$, the cuttings will be transported upward together with the fluid and would not settle on the low-side annular wall.

Because the cuttings density is usually higher than that of the drilling fluids, drilled cuttings will usually settle downwards within the drilling fluids. Fig. 3.3.2 demonstrates the settling of a cutting in a deviated wellbore. We may divide the cuttings settling velocity into two components. One is $v_{sa}$ which is parallel to the hole axis and the other is $v_{sva}$ which is vertical to the hole axis. $v_{sva}$ can be written as:

$$v_{sva} = v_s \cdot \sin(\Phi)$$  \hspace{1cm} (3.3.5)

Eq. 3.3.5 demonstrates that for any non-zero cuttings settling velocity, which is the general case, the cuttings will settle towards the low-side wall of a deviated annulus at the velocity of $v_{sva}$. As the hole angle increases, $v_{sva}$ will be increased until reaching $90^\circ$ hole angle, where the cuttings will settle towards the low side wall of a deviated annulus at the cuttings settling velocity $v_s$. In this case the cuttings may settle on the low side wall of the annulus as soon as the cuttings are injected into the wellbore, which were confirmed by previous researchers\(^{(19,20)}\). In vertical wells, $v_{sva}$ is zero i.e. no cuttings bed will be formed on the annular wall. In actual drilling practices it is exactly the case.

The above analysis shows that cuttings have a tendency to settle towards the low side wall of a deviated annulus. Because of the limited annular clearance, cuttings may settle on the low side annular wall sooner or later. As has been known from the literature review that the major problem for deviated hole cleaning has been the formation of a cuttings bed on the low side annular wall, therefore, how to remove the cuttings settled there is the main concern. In the following section the forces acting on a cutting resting on the low side annular wall is analysed and the criteria for the initiations of cuttings movement are defined.

### 3.3.2 A cutting resting on the low-side annular wall

(1) **Forces acting on the cutting**\(^{(26)}\)

The forces acting on a cutting resting on the low-side annular wall are shown in Fig. 3.3.3. Except for the lift force $F_L$, drag force $F_D$ and the gravity force $F_g$, another force acting on
Fig. 3.3.2 Settling of cuttings in a deviated wellbore

As a general case, both the fluid drag force $F_D$ and the fluid lift force $F_L$ will contribute to the suspension of cuttings within the deviated wellbore. However, it may be easily seen that at the point of emergence, fluid lift force should balance the axial component of the normal force, $N$, and the fluid drag force should be equal to the axial component of the fluid lift force. Substituting Eqs. 3.3.3 and 3.2.1 into Eq. 3.3.9, the criterion for cuttings to be removed from the deviated wellbore is determined.

Fig. 3.3.3 Forces acting on a cutting resting on the low-side wall of the annulus in a deviated wellbore
the cutting is the friction force between the cutting and the low-side wall of the annulus, which can be expressed as:

$$F_t = (F_L \cdot \sin(\Phi) - F_g) \cdot f_i$$  (3.3.6)

It can be easily understood that if $F_L \geq F_g \cdot \sin(\Phi)$, the friction force $F_t$ will be zero. This is the case at which, the cuttings are suspended within the drilling fluid.

(2) Analysis of the movements of a cutting resting on the low-side annular wall

Based on the forces acting on the cutting, it is very clear that there are three ways for the cutting to be removed from a deviated annulus.

a. Cuttings suspension

As a general case, both the fluid drag force $F_D$ and the fluid lift force $F_L$ will contribute to the suspension of the drilled cuttings. When the cuttings have just been suspended within the drilling fluid, the force balance equation should be:

$$F_L \cdot \sin(\Phi) + F_D \cdot \cos(\Phi) \geq F_g$$  (3.3.7)

However, it may be easily seen that at the point of suspension, the fluid drag force should just balance the axial component of the gravitational force when the equilibrium conditions have reached:

$$F_D = F_g \cdot \cos(\Phi)$$  (3.3.8)

Substituting Eq. 3.3.8 into Eq. 3.3.7, we have:

$$F_L \geq F_g \cdot \sin(\Phi)$$  (3.3.9)

Eq. 3.3.9 shows that if the fluid lift force $F_L$ is greater than $F_g \sin(\Phi)$, the cuttings will be lifted off the low-side wall of the annulus into the flow stream and be transported within the drilling fluid. Substituting Eqs. 3.3.3 and 3.2.1 into Eq. 3.3.9, the criterion for cuttings suspension can be derived as:

$$C_L \cdot A_L \cdot \frac{\rho_r \cdot v_p^2}{2} \geq V_i \cdot (\rho_i - \rho_r) \cdot g \cdot \sin(\Phi)$$  (3.3.10)
b. **Cuttings rolling**

Under the action of the fluid drag force $F_D$, the cutting tends to roll upward along the low-side annular wall. The critical condition for cuttings rolling should be defined as:

$$F_D \cdot MN \geq F_{ga} \cdot OM$$  \hspace{1cm} (3.3.11)

i.e.,

$$C_D \cdot A_p \cdot \frac{\rho_r \cdot v_p^2}{2} \cdot MN \geq V_s \cdot (\rho_s - \rho_r) \cdot g \cdot \cos(\Phi) \cdot OM$$  \hspace{1cm} (3.3.12)

c. **Cuttings sliding forward**

Cuttings may slide forward along the low-side wall of the test annulus if the following condition is satisfied:

$$F_D \geq F_{ga} + F_f$$  \hspace{1cm} (3.3.13)

That is:

$$C_D \cdot A_p \cdot \frac{\rho_r v_p^2}{2} \geq F_g \cos(\Phi) + (F_g \sin(\Phi) - C_L A_L \frac{\rho_f v_p^2}{2}) \cdot f_s$$  \hspace{1cm} (3.3.14)

3.3.3 The MTV models for deviated hole cleaning

In the above discussions, the initiations of the movement of cuttings resting on the low-side annular wall have been physically defined. Using these different criteria, the MTV models are defined in the following analysis.

a. **The MTV model for cuttings suspension**

Eq. 3.3.10 defined the criterion for cuttings suspension. It can be easily concluded that the minimum fluid velocity required to satisfy Eq. 3.3.10 should become:

$$C_L \cdot A_L \cdot \frac{\rho_r \cdot v_p^2}{2} = V_s \cdot (\rho_s - \rho_r) \cdot g \cdot \sin(\Phi)$$  \hspace{1cm} (3.3.15)

This is the MTV model for cuttings suspension.
b. The MTV model for cuttings rolling/sliding

Eq. 3.3.12 has defined the initiation of cuttings rolling. However, in actual practice, a cuttings bed rather than a single cutting will settle on the low-side annular wall. It is obvious that the highly possible moving pattern may be a moving bed. In fact, if the following assumptions are made:

i. The cuttings are spherical particles;

ii. Both fluid drag force and fluid lift force are acting on the centre of the cuttings.

\[ \overline{MN} = \overline{OM} \] and Eq. 3.3.12 may become:

\[ C_D \cdot A_p \cdot \frac{\rho_f \cdot V_p^2}{2} \geq V_s \cdot (\rho_s - \rho_f) \cdot g \cdot \cos(\Phi) \]  \hspace{1cm} (3.3.16)

This shows that Eq. 3.3.16 is a special case of Eq. 3.3.14 when \( f_s \) is equal to zero. Therefore, it may be realised that the criterion for cuttings sliding forward is a generalised case for both cuttings rolling and cuttings sliding. In actual practice, it may be extremely difficult to identify whether the cuttings are rolling or sliding forward along the low-side annular wall. Thus, in the present study, Eq. 3.3.14 has been used to define cuttings rolling/sliding.

From Eq. 3.3.14, it may be easily concluded that the minimum transport velocity to initiate cuttings movement by cuttings rolling is expressed as:

\[ C_D \cdot A_p \cdot \frac{\rho_f V_p^2}{2} = F_g \cos(\Phi) + (F_g \sin(\Phi) - C_L A_L \frac{\rho_f V_p^2}{2}) \cdot f_s \]  \hspace{1cm} (3.3.17)

The fluid velocity which can satisfy Eq. 3.3.17 is defined as the MTV for cuttings rolling/sliding. This is the MTV model for cuttings rolling/sliding.

It needs to be pointed out that in the derivations of the MTV models, no assumptions have been made for the fluid rheological properties and fluid flow regimes. Therefore, they can be used for any fluids and in any flow regime. However, in the present study, a single cutting was assumed. The interaction between the different cuttings and cohesiveness and adhesion between the cuttings are not considered.
3.4 Fluid rheological models

The MTV models for deviated hole cleaning have been derived in the above analysis. In the literature review, it is known that the rheological properties of the drilling fluids played a great role in cuttings transport. Fluid rheology is extremely important to field engineers due to the fact that fluid rheological properties are the few adjustable parameters during drilling operations. Drilling fluids usually behave as non-Newtonian in rheological properties. Unlike Newtonian fluids, the viscosity of drilling fluids is shear dependent. The effective viscosity of non-Newtonian fluids depends on the shear deformation experienced by the fluids. Various rheological models have been developed to describe the flow behaviour of different fluid materials. However in the petroleum industry, the commonly used models are power-law and Bingham plastic models. Recently based on the characterisation results of drilling fluid samples from the field, it is realised that drilling fluids may be best described by Herschel-Bulkley model in rheological properties. In this section, the various fluid rheological models are discussed.

3.4.1 Newtonian fluids

For Newtonian fluids, the shear stress and shear strain deformation are described in cylindrical co-ordinate system by:

\[ \tau_r = -\mu \frac{d\nu_z}{dr} \]  \hspace{1cm} (3.4.1a)

where "-" is used when \(d\nu_{zr}/dr > 0.0\) and "+" is used when \(d\nu_{zr}/dr < 0.0\).

For convenience, Eq. 3.4.1 is quite often expressed as:

\[ \tau = \mu \cdot \gamma \]  \hspace{1cm} (3.4.1b)

where \(\mu\) is the fluid viscosity, which is a constant.

3.4.2 Power law fluids

Power law fluids are shear dependent. As the shear rate acting on the fluid increases, the fluid viscosity will be decreased. In a cylindrical co-ordinate system, the relation between shear stress and shear rate is expressed as:
where “-” is used when \( \frac{dV_z}{dr} > 0.0 \) and “+” is used when \( \frac{dV_z}{dr} < 0.0 \). In practice, it is usually expressed as:

\[
\tau = K \cdot (\gamma)^n
\]  

(3.4.2b)

For non-Newtonian fluids, the fluid effective viscosity varies with the shear rate imposed on the fluid. For a given shear stress and stress rate, the fluid effective viscosity is defined as:

\[
\mu_e = \frac{\tau}{\gamma}
\]  

(3.4.3)

Substituting Eq. 3.4.2b into the above equation, the effective viscosity for power law fluids is derived as:

\[
\mu_e = K \cdot (\gamma)^{(n-1)}
\]  

(3.4.4)

### 3.4.3 Bingham plastic fluids

Bingham plastic fluids are characterised by a fluid yield point. The so called yield point is the shear stress required to initiate shear on the fluid. If the shear stress acting on the fluids is less than the yield point, the fluid will not be sheared. It is also the force required to make the fluid in motion. This model is expressed as:

\[
\tau_z = \tau_y - \mu_p \frac{dV_z}{dr} \quad (|\tau_z| \geq \tau_y)
\]  

(3.4.5a)

where “-” is used when \( \frac{dV_z}{dr} > 0.0 \) and “+” is used when \( \frac{dV_z}{dr} < 0.0 \). For simplicity, Bingham plastic fluid is expressed as:

\[
\tau = \tau_y + \mu_p \cdot \gamma
\]  

(3.4.5b)

Similarly as the case for power law fluids, the fluid effective viscosity for Bingham plastic fluids is expressed as:

\[
\mu_e = \frac{\tau_y + \mu_p}{\gamma}
\]  

(3.4.6)
3.4.4 Herschel-Bulkley model

Herschel-Bulkley model is the modified power law model with a non-zero yield point, which can be written as follows in cylindrical co-ordinates:

\[ \tau_z = \mp \tau_y - K \left( \frac{dv_z}{dr} \right)^{n-1} \left( \frac{dv_r}{dr} \right) \left( |\tau_r| \geq \tau_y \right) \] (3.4.7a)

where "-" is used when \( dv_z/dr > 0.0 \) and "+" is used when \( dv_z/dr < 0.0 \). It is often expressed as:

\[ \tau = \tau_y + K \cdot (\gamma)^n \] (3.4.7b)

The effective viscosity for Herschel-Bulkley fluids is:

\[ \mu_e = \frac{\tau_r}{\gamma} \] (3.4.8)

Comparing the four different fluid rheological models, it can be easily seen that Herschel-Bulkley model is actually a generalised expression of all the other three models. For example, when \( \tau_y = 0.0 \), \( n = 1.0 \), and while setting \( \mu = K \), Eq. 3.4.7b will become the Newtonian fluid model as Eq. 3.4.1b. As \( \tau_y = 0.0 \) and \( n \neq 1.0 \), it will become the power-law model, which is expressed as Eq. 3.4.2b. It will become Bingham plastic model as Eq. 3.4.5b when \( n = 1 \) and \( \mu_p = K \).

It can be seen that Herschel-Bulkley model covers all the three commonly used rheological models. Because of the above characteristics of the Herschel-Bulkley rheological model, it should be the best model to be used in the drilling industry. Therefore, modelling of annular flow of Herschel-Bulkley fluids has been carried out in the present study.
CHAPTER 4
EXPERIMENTAL FACILITIES AND PROCEDURES

It has been known that drilled cuttings transport in deviated annuli is a very complicated process. It is impossible at the present time to derive the transport models only from the theoretical aspect. Thus, parallel investigations from both theoretical and experimental aspects, are required to tackle this problem. Theoretical study tries to identify the various influential parameters and the various cuttings transport mechanisms, and to establish the physical force balance equations. Experiments provide the necessary experimental data required for the theoretical models. In this chapter, the experimental programme and experimental techniques are presented.

Previously the experimental investigation into drilled cuttings transport has mainly concentrated on the following three aspects:

- The objectives of the experiment
- The experimental parameters
- Experimental facilities including the video recording and data acquisition system

In this chapter, detailed descriptions are presented of the various aspects concerned. The experimental rig, which was purposely built in the Department of Petroleum Engineering at Heriot-Watt University for the study of drilled cuttings transport in deviated wells, is described. The detailed experimental procedures are also presented.

4.1 Objectives of the experiments

Drilled cuttings transport is actually a problem of solid-liquid two phase flow. However unlike the solid-liquid two phase flow in hydraulic transport and sediment transport in open channels, cuttings transport in deviated wellbores is complicated by the following aspects:

- The carrier fluid is non-Newtonian in rheological properties.
• Cuttings transport happens in an annulus, not in a circular pipe or open channels.
• The drill pipe may locate at any eccentric position in the wellbore.
• The drill pipe may be rotated at various rotary speeds.
• The wellbore may be at any hole angle from $0^\circ$ to $90^\circ$ from the vertical.
• A range of sized particles are transported simultaneously.

Because of the complex geometry and the various operating conditions involved, the behaviours of the cuttings inside a drilling annulus are very complicated and the various factors affecting hole cleaning efficiency are interrelated in a complicated manner. It is obvious that to clearly define the objectives of the experiments is very important.

4.1.1 Characterising the behaviour of cuttings movement in deviated wells

Cuttings movement in a deviated annulus is complicated and has not been well understood though much effort has been made. In the present study new concepts have been used to define the minimum transport velocity required for adequate hole cleaning. Two criteria for the initiations of cuttings movement in inclined annuli have been identified. One is for the initiation of cuttings rolling and the other is for the initiation of cuttings suspension. It is obvious that cuttings transport behaviours in deviated wells are much more complicated than simply rolling or suspension. In fact cuttings are moving randomly and in most cases, cuttings are moving in a mixture of rolling, suspension and moving bed. Therefore cuttings movements need to be described by various simplified flow patterns so that the two minimum transport velocities for efficient deviated hole cleaning can be determined accurately and consistently. In order that the cuttings movements can be simply described by various flow patterns, the cuttings behaviours must be carefully observed and characterised during the cuttings transport experiments.

4.1.2 Evaluating the effects of various drilling parameters on cuttings transport efficiency

How the various parameters affect cuttings transport in deviated wellbores has not been well understood. Sometimes there is obvious confusion about the effect. Opposite opinions
do exist. For example, one says laminar flow is favourable to cuttings transport and another author said turbulent flow would improve hole cleaning efficiency as can be seen in Table 2.9.1. It is envisaged that the effects of the various parameters are interrelated in a complicated manner. At different simulated drilling conditions, the effect of one parameter may be quite different from another. Therefore, in the present experiment a wide range of parameter values are used so as to try to identify the different interrelated effects of the different parameters on deviated hole cleaning efficiency.

4.1.3 Establishing a data base for the MTV models

The establishment of the MTV models developed for deviated hole cleaning needs an extensive number of experimental data. To build up an experimental data base is one of the major purposes of the present experimental programme.

4.1.4 Developing guide-lines for the design of cuttings transport

In the field whenever there is any hole cleaning problem, it is crucial to know how the hole cleaning can be affected if one parameter is being changed. How can the hole be fully cleaned at the given drilling conditions so that the drilling process can proceed smoothly? How can the wellbore be drilled safely with minimum cost? Taking the experimental results as a basis, some guide-lines are developed to help field engineers design and adjust the drilling fluid properties properly.

4.2 Experimental parameters(48)

Cuttings transport experiment is a study of cuttings transport behaviours at simulated drilling conditions. It is evident that the more realistically the actual drilling conditions are simulated, the more valuable the results are. Based on this point of view, the experiments have been designed to simulate the actual drilling conditions as realistically as possible. The various parameters investigated are summarised as follows:
4.2.1 Annular fluid velocity

Annular fluid velocity is the most important parameter affecting drilled cuttings transport. In order to investigate the transport process extensively and also based on the facilities available, the annular fluid velocity is varied in the range of 0.0 to 420 ft/min.

4.2.2 Fluid rheological properties

Power law model has been chosen to characterise fluid rheological properties for the evaluations of the MTV models and for the study of deviated hole cleaning efficiency because of the fact that the rheological properties of the polymer fluids used in the present study are best described by power law model. However, it needs to be pointed out that the fluid rheograms rather than the fluid n/K values are directly used for the analysis of the hole cleaning efficiency of different fluids.

For the reason that actual observations are used during the present studies, it is proposed that water based polymer fluids are used to simulate drilling fluids at the first stage of our experiments. Thereafter, bentonite fluids are used so that the drilling fluids can be simulated more realistically. In fact, these fluids were formulated based on the characterisation of a wide range of actual drilling fluids used in the North Sea. The simulated drilling fluids have well represented the actual drilling fluids, which can be seen in chapter 5 (Fig. 5.5.5). The various fluids and their rheological properties used in the present experiments are tabulated in Table 4.2.1. It needs to be pointed out that in addition to the fluids used in Table 4.2.1, special tests have also been conducted using fluid viscosity reductions. First of all, formulate a relatively high viscous fluid and run the experiment at some specified hole angles. Then the fluid is gradually diluted and the experiments are run at the same hole angles using these diluted fluids. Therefore, the effect of fluid viscosity on hole cleaning efficiency can be well simulated.
Table 4.2.1 The simulated fluids and their properties for the cuttings transport experiments

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Compositions$^{(1)}$ (gram/litre)</th>
<th>n(2)</th>
<th>K(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Water only</td>
<td>1.0</td>
<td>0.012</td>
</tr>
<tr>
<td>#2</td>
<td>Lo.Vis CMC: 14.0</td>
<td>1.03</td>
<td>0.40</td>
</tr>
<tr>
<td>#3</td>
<td>Hi.CMC: 2.5 + XC: 0.15</td>
<td>0.63</td>
<td>4.0</td>
</tr>
<tr>
<td>#4</td>
<td>Hi.CMC: 4.0 + XC: 0.3</td>
<td>0.52</td>
<td>16.50</td>
</tr>
<tr>
<td>#5</td>
<td>Ben: 28.53 + Hi.CMC: 2.5 + XC: 0.15</td>
<td>0.33</td>
<td>31.0</td>
</tr>
<tr>
<td>#6</td>
<td>Hi.CMC: 5.0 + XC: 2.0</td>
<td>0.45</td>
<td>28.0</td>
</tr>
<tr>
<td>#7</td>
<td>Hi.CMC: 7.0 + XC: 2.0</td>
<td>0.44</td>
<td>46.0</td>
</tr>
<tr>
<td>#8</td>
<td>Ben: 28.53 + Polyvis: 2.0</td>
<td>0.14</td>
<td>260.0</td>
</tr>
</tbody>
</table>

Note: (1) Ben: Wyoming Bentonite API Specification; CMC: Carboxymethyl Cellulose; Hi.CMC: High Viscosity CMC; Lo.Vis CMC: Low Viscosity CMC; Polyvis: Mixed Metal Hydroxide. 

(2) n: Non-Newtonian Index of power law fluid; K: Consistency Index of Power Law fluids, Dyne-s$^6$/cm$^2$ 
These are the approximate values.

4.2.3 Simulated cuttings size

Cuttings size is a very important parameter affecting drilled cuttings transport. In order to study the effects of cuttings characteristics on cuttings transport, a large variety of simulated or actually drilled cuttings, both in size and in shape, have been used by previous researchers as discussed in Appendix A4.1. In the present study gravel sand is used as the simulated drilled cuttings due to the following reasons:

- Gravel sand is easier to obtain and is relatively cheaper.
- Gravel sand is similar to actually drilled cuttings.
- Gravel sand is quite strong so that the degradation during the experiments is not very serious.

In order to simulate the effects of cuttings size more realistically, two main cuttings sizes have been chosen based on an extensive analysis of the actually drilled cuttings from the
North Sea\textsuperscript{(49)}, which is also presented in Appendix A4.1. The two main cuttings sizes are 1.7-2.0 mm and 2.8-3.35 mm. For the convenience of discussions, 1.7-2.0 mm cuttings are named as the small cuttings and 2.8-3.35 mm cuttings are named as the big cuttings. Some other cuttings sizes have also been selected which covers 0.08 to 1.2 mm. The density of the gravel sand is 2.63 g/cm\textsuperscript{3}.

4.2.4 Annular size

Three annular sizes have been used in the present experimental programme to study the effect of annular size on hole cleaning efficiency at various hole angles, including:

a. 13.7 x 6.10 cm
b. 13.7 x 8.89 cm
c. 13.7 x 3.34 cm

For convenience, the annulus is defined as big annulus for a big annular clearance and small annulus for a smaller annular clearance. Therefore in the present case, 13.7 x 8.89 is named as the small annulus and 13.7 x 6.10 as the big annulus. 13.7 x 3.34 cm annulus is called as super annulus.

4.2.5 Hole angle

Based on the facilities available, the hole angle can be varied from 0° to 90° from the vertical. The following specified hole angles are used: 0°, 30°, 40°, 50°, 60°, 75°, and 90°. So, the effects of hole angle on cuttings transport can be widely covered.

4.2.6 Pipe eccentricity

The various pipe eccentricities used are: 30\%, 50\%, -50\% and 70\%. The definitions of pipe eccentricity can be seen in Fig. 2.4.1. A positive eccentricity is defined as the pipe eccentricity when the drill pipe offsets towards the low side wall of a deviated annulus and the negative eccentricity is defined as the case when the drill pipe offsets towards the high side wall of a deviated annulus.
4.2.7 Pipe rotary speed

The drill pipe can be rotated from 0 to 200 rpm. The pipe rotary speeds used are: 0, 60, and 120 rpm. It needs to be pointed out that in the present experimental programme, both pipe axial rotary speed and pipe orbital motion are experimentally investigated.

4.2.8 Cuttings concentration

Four different cuttings concentrations have been used in the present experimental studies, including 1%, 2%, 3% and 4% by volume. This, in fact, has covered a wide range of field operations. Fig. 4.2.1 has illustrated the relationship between rate of penetration and the cuttings concentration in a 12-1/4" hole. In fact, we have used quite low pump rates in the calculations. Considering the actual pump rate used in the field, which is about 800-1000 gpm, 4% cuttings concentration will correspond to a high rate of penetration though some operators drill up to 180 - 250 ft/hr.

![Fig. 4.2.1 Rate of penetration versus cuttings concentration in 12 1/4" hole](image)

4.3 Experimental facilities

In order to simulate cuttings transport effectively, the following requirements must be satisfied by the experimental facilities:

- The test annulus must be long enough so that the annular flow can reach steady state conditions, i.e. exit and entrance effects can be allowed for.
The experimental apparatus must be flexible enough so that the various drilling conditions can be simulated realistically.

During the present study, a cuttings transport rig has been purposely built which is long enough to establish a steady flow and flexible enough to simulate the various drilling operations. In addition some auxiliary instrumentation has been installed such as the video recording system, data acquisition system, which are described as follows:

4.3.1 The main cuttings transport rig

The cuttings transport rig for the investigations of deviated hole cleaning has been shown in Fig. 4.3.1. The rig is especially built to simulate a deviated/vertical borehole. A proposed slurry (a mixture of drilling fluid + simulated cuttings) can be circulated through the annulus between the inner and outer tubes. The rig is mainly composed of:

a. Cuttings transport testing section

The testing section can be set at any angle between 0° and 90° to simulate directional drilling operations. The total length of the column is 21 ft. It is basically composed of a perspex transparent outer tube and a stainless steel inner tube. Three different inner tube sizes are used during the experiments to simulate the effects of annular geometry on cuttings transport efficiency. The three annuli are:

13.7 x 8.89 cm
13.7 x 6.10 cm
13.7 x 3.34 cm

The inner tube can be rotated with a variable speed motor in the range of 0 - 200 rpm to simulate drill pipe rotation. It can also be set at different positions to simulate the concentric/eccentric annulus. In the present state it can be arranged at 30%, 50%, -50% and 70% eccentricities. If required, some special flanges can be made to simulate other eccentricities from 0 up to ±100%.
Basic Parameters

Outer tube size: 137 mm
22 ft length
0 - 90 Degrees

Inner tube size: 88.9 mm, 61 mm & 33.4 mm

Rotary speed: 0 - 150 rpm
Flowrate: 0 - 300 gpm
Tank capacity: 500 Gallons

Fig. 4.3.1 Schematic diagram of the cuttings transport rig
The experimental rig was also designed for the drill pipe to be rotated orbitally so that the effect of drill pipe orbital motion on drilled cuttings transport efficiency can be investigated.

b. Fluid tanks

There are two main fluid tanks with a total capacity of about 2,000 litres (about 500 gallons) for the experiments. Inside the tanks the simulated drilling fluids can be mixed. Then the simulated cuttings can be added into the tank to get ready for the cuttings transport experiment. Inside each of these two tanks there is a paddle mixer which is used to mix the simulated drilling fluids and make the simulated cuttings in full suspension. The mixers can be rotated at about 0 to 400 rpm so as to produce the turbulence required to suspend the cuttings within the fluid.

c. Pump

The pump is a centrifugal pump with a maximum output flow rate of 300 gpm. The pump is driven by a variable speed motor. Therefore the flow rate can be adjusted continuously by changing the speed of the variable speed motor. Another advantage of the variable speed motor is that the rotary speed of the pump is used to change the flow rate so that the pump is not necessary to be run at maximum speed all the time. This has proved to be very effective for preventing the simulated cuttings from degrading during the experiments.

d. Measuring and recording system

There is a video camera racking system mounted on the annular column. The video camera can be moved along an 8 ft section in the middle of the column by remote control. The video picture can be displayed on a colour monitor, together with other test parameters, and recorded when necessary.

A differential pressure transducer is used to measure the pressure difference across an approximate 7 ft section in the middle section of the column and another pressure transducer is used to monitor the absolute pressure inside the column for safety purposes.
A magnetic flow meter is installed on the return line of the flow loop to measure the circulating flow rate through the column and allow the calculation of the mean fluid velocity in the annulus.

4.3.2 Auxiliary instruments

a. A HAAKE-VT 181 viscometer is used to measure the fluid rheological properties under the corresponding temperatures of the fluid samples taken during the experiments in the range of shear rates of 5-424 1/s. A Fann VG viscometer is also used to measure the fluid rheological properties at the room temperature.

b. A density bottle is used to measure the densities of the test fluids and sand materials.

4.4 Experimental procedures

A standard experimental procedure was developed for the cuttings transport experiments after some pilot tests carried out at the initial stage of the experiments:

a. Before each test, the desired gravel size range is defined for the test and the gravel sand is weighed and washed. Based on the pilot tests, the test fluid with the preferred fluid rheogram was mixed directly in the two tanks. After the mixing process was completed, the fluid was left for more than eight hours to allow the release of the trapped air. Sand of required quantity was then mixed with the simulated drilling fluid in the tanks.

b. The two mixers in the tanks were rotated for about 20 minutes before starting the test so as to pre-shear the fluid and to make the sands uniformly suspended within the fluid. During this period, the column was set to the desired angle, the recording system checked and adjusted if necessary. All the by-pass valves would be closed.

c. Start the pump at maximum flow rate. Then wait for some time until a stable flow condition has been reached. Then, take all the readings and operate the video camera, so as to record the flow patterns at different hole sections.
d. After that, decrease the flow rate and repeat the above process until a very thick stationary cuttings bed is formed on the low-side wall of the annulus or the cuttings bed starts sliding downwards. Then, increase the flow rate to check the above results.

e. During the tests, three fluid samples were taken respectively at the beginning of the test, at the minimum flow rate and at the end of the test. The corresponding temperatures were measured.

f. After the test, the rheological properties of the three fluid samples were measured using the HAAKE VT 181 viscometer at the corresponding temperatures and by Fann VG viscometer at room temperature.

g. Set the column at another preferred hole angle and adjust the fluid rheological properties to the same level as before. Repeat the above process until completing the whole group of experiments which is from 0° to 90° from the vertical.

h. After completing the group of tests, the fluid was drained. Two special baskets are then put into the tanks. The sand was collected in the two cuttings collection baskets using water as the circulating fluid. The cuttings were dried, re-screened and weighed. The weighted average percentages were recorded. The video recording was reviewed so that the various flow patterns could be analysed.

4.5 Determinations of the various experimental parameters

4.5.1 The minimum transport velocity

During the present experiments, two critical velocities are obtained. One is the minimum transport velocity for the initiation of cuttings rolling and the other is the minimum transport velocity for the initiation of cuttings suspension. The determinations of these two MTVs required for complete hole cleaning are described in detail in the proceeding chapter.

4.5.2 The simulated cuttings diameter

As we know that the simulated cuttings will be degraded during the cuttings transport process, the simulated cuttings are not only degraded in size but also it will make
necessary the assumption of a uniform cuttings a size distribution. Thus, cuttings size must be corrected before it is used in the establishment of the MTV models.

Considering the simplicity and practicability, it was decided that the weighted average sieve diameter be used as the sand equivalent diameter throughout the experiments. The procedure to determine the equivalent simulated cuttings size is as follows:

a. Before each group of tests, take some simulated cuttings sample. After the sample becomes dry enough, screen the sample and record the weighted size distribution of the sample.

b. After each group of tests, dry the cuttings, screen and record the weighted percentage of the simulated cuttings.

c. Calculate the weighted average diameters of the two sand samples using the following equation:

\[
d_i = \frac{\sum \left( \frac{d_i + d_{i+1}}{2} \right) (p_{i+1} - p_i)}{100}
\]

(A4.1.2)

d. Take the equivalent diameter of the sample taken before the experiments as the equivalent diameter for the first test and take the equivalent diameter after the sand has been used as the equivalent diameter for the last test of the experiments. Based on the assumption that the simulated cuttings are equally degraded during each test, the equivalent diameters for all the other tests can be determined.

4.5.3 The fluid rheological properties

During the experimental process, because of the changes in fluid temperature and time dependent properties of the drilling fluid, the fluid rheological properties will change. Thus, three fluid samples have been taken for each test, at the beginning, in the middle, and at the end of each test run. The corresponding temperatures were measured. The rheological properties of the three fluid samples are then measured at the corresponding temperatures by a HAAKE VT 180 viscometer and at room temperature by the Fann VG viscometer. The fluid properties were taken by the average of the three fluid samples.
4.5.4 Friction coefficient between the cuttings and the annular wall

As shown in Eq. 3.3.17, the MTV for cuttings rolling/sliding is affected by the friction coefficient between the cuttings and the low side wall of a deviated annulus. The static friction coefficient between the cuttings and the annular wall at wet conditions is measured according to the following procedure(26):

a. Set the annulus in the horizontal position;
b. Circulate the cuttings with the fluid through the annulus until a thin layer of cuttings bed has been formed on the low-side wall of the annulus. Then stop circulation.
c. Slowly raise one end of the annulus from the horizontal position until the cuttings bed starts sliding down along the low side wall of the annulus.
d. Measure the hole angle of the annulus and obtain $\Phi_c$.
e. The friction coefficient between the annular wall and the cuttings is determined by the following formula:

$$f_s = \frac{1}{\tan(\Phi_c)} \quad (4.5.1)$$
CHAPTER 5
PRESENTATION OF THE EXPERIMENTAL RESULTS

The extensive experimental programme discussed in the preceding chapter has been carried out. In this chapter the experimental results are presented. First of all, the various phenomenon of the cuttings movements at different simulated conditions are described by simplified flow patterns. Then, the two criterion for the initiations of cuttings movements in deviated annuli are defined. Based on the experimental data, the effects of the various parameters affecting deviated hole cleaning efficiency are analysed and discussed. Further details can be seen from paper publications (34-36).

5.1 Description of the cuttings behaviours observed

In the present experiments, visual observation is used to investigate cuttings transport process. In order that the cuttings movements in the annulus is clearly observed, transparent perspex outer tube and transparent simulated drilling fluids have been used. During the experiments, the cuttings behaviours at various simulated drilling operations are carefully observed, which are also recorded by a video recording system. At different hole angles and operating conditions, different phenomenon have been observed for the movement of the drilled cuttings. In this section a general description is presented. Because of the different cuttings behaviours at different hole angles, the description is made according to different hole angles.

5.1.1 General description

At very high fluid velocities, all the cuttings are suspended within the fluid and transported up to the surface in full suspension even at highly deviated boreholes. The cuttings are uniformly distributed around the hole axis even at high hole angles when high viscosity
fluid was used. As the fluid velocity decreases, more and more cuttings are accumulated in the lower half of the deviated annulus. The flow mixture becomes heterogeneous suspension with more cuttings in the lower half of the annulus than that in the higher half of the deviated annulus. Further reducing the fluid flow rate, some cuttings start to settle on the low side wall of the annulus and then the cuttings may immediately jump into the flow stream again. This is the so called cuttings recycling process as defined by Iyoho (19) and Tomren et al. (20). However, cuttings saltation only occurs when low viscosity fluid or water was used as the simulated drilling fluid.

As the fluid velocity is further reduced, more cuttings will settle on the low-side wall of the deviated annulus. Some of the cuttings are not able to jump into the flow stream again. However the cuttings are still moving upward in the form of moving bed or rolling. If the annular fluid velocity is continuously reduced, some cuttings become stationary in the annulus and could not be removed. This is the case where a stationary cuttings bed is formed.

As the flow rate further decreases, the stationary cuttings bed becomes thicker and thicker. However at the hole angles of below 60 degrees, this cuttings bed may start sliding downward along the low side annular wall if the fluid velocity is below a certain limit.

In the case of a thick cuttings bed being formed on the low side wall of a deviated annulus, as the fluid velocity increases, this cuttings bed is gradually eroded. The cuttings bed becomes thinner and thinner until one point has been reached where the stationary cuttings bed starts to move upward either in sliding or in rolling. Further increasing the fluid flow rate, the moving bed may be broken into separated moving bed. Gradually the cuttings are thrown away into the flow stream. Cuttings saltation occurs. Increasing the flow rate further, all the cuttings are suspended within the fluid. The flow becomes heterogeneous flow until homogeneous flow state is reached where the cutting are uniformly suspended around the hole axis.
5.1.2 At vertical and near vertical hole angles (0 to 15°)

At this range of hole angles, no cuttings bed is formed on the low side wall of the annulus. At high flow rate the cuttings are uniformly distributed around the hole axis. As the flow rate gradually decreases, more and more cuttings are accumulated in the lower half of the annulus. Further reducing the flow rate, some cuttings may start sliding down along the low side borehole wall. However there are still some cuttings being transported up to the surface within the flow stream. Continuously decreasing the flow rate a point will be reached at which all the cuttings will start sliding downward and no cuttings can be removed.

5.1.3 At low hole angles (15 to 40°)

As the hole angle increases from the vertical, cuttings transport becomes worse. A thin cuttings bed may be formed on the low side annular wall. Though the behaviours of cuttings movements are quite similar to that at vertical or near vertical wells, the MTV required to clean the hole will be greatly increased for high hole angle wells.

5.1.4 At critical hole angles (40° to 60°)

40° to 60° hole angles were defined as critical hole angles by previous researchers. In the present study this has been further confirmed. Based on the present experimental results, at this range of hole angles not only a stationary cuttings bed can be formed on the low side annular wall, this bed may slide downwards if the fluid velocity is not high enough. In actual drilling practices this is quite dangerous situation for the sliding down cuttings bed may easily cause packing off and stuck pipe. As discussed later, it is these hole angles which are the most difficult hole angles to be cleaned.

In actual drilling practices, annular fluid velocity must exceed the velocity at which cuttings sliding down occurs. Whenever circulation is going to be stopped, the hole must be well cleaned so that there are minimal cuttings left in the annulus in order to prevent stuck pipe.
5.1.5 At high hole angles (above 60°)

At high hole angles the cuttings have a strong tendency to settle toward the low side annular wall. The cuttings may settle on the low side annular wall as soon as they are injected into the annulus. These settling cuttings will soon be suspended within the fluid flow stream at high flow rate. However a homogeneous cuttings suspension is difficult to be achieved even at high flow rate due to the greater tendency of the cuttings settling towards the low-side annular wall. When the flow rate is decreased from high to low, cuttings may start to settle down on the low side wall of the annulus. As stated above, these cuttings may still be cleaned out of the borehole by cuttings rolling/sliding.

Further decreasing fluid flow rate, some cuttings may become stationary on the low side wall of the annulus. A thick stationary cuttings bed may be formed but this cuttings bed will not slide downward toward the hole bottom even when the circulation is stopped.

5.1.6 Special observations of the cuttings behaviours in deviated wells

During the cuttings transport experiments, some interesting phenomenon have been observed, which are summarised as follows:

- Various flow patterns of the cuttings movements have been observed, including cuttings suspension, rolling or sliding, and stationary cuttings bed, etc., which are discussed in detail in the next section.
- More and more cuttings are transported near the low-side annular wall as long as the annular fluid velocity decreases.
- The turbulence of the circulating fluid has a great impact on the stability of the cuttings. The stronger the fluid turbulence, the more unstable the cuttings movement. When water is used as the drilling fluid, the cuttings in the annulus are quite unstable. The cuttings are mostly transported as separated moving beds, clusters, dunes. A continuous moving bed can hardly be formed.
- When the simulated fluid is a viscous fluid (fluids #4 to #8), the cuttings in the annulus are quite stable. Instead of being transported as separated moving bed,
clusters, dunes, the cuttings are transported either as full suspension, or as a continuous moving bed. Below a certain velocity, a continuous stationary cuttings bed is formed as long as the hole angle is above 30°.

- For hole angles of 40° to 60°, not only a thick cuttings bed may be formed but also the bed will slide downward along the low side annular wall if the fluid velocity is not high enough. This is a potentially dangerous situation during drilling operations since it can lead to packing off, stuck pipe, and possibly fractured formation.

- The experiments demonstrated that two cuttings transport mechanisms, i.e. cuttings rolling or sliding and cuttings suspension, do dominate hole cleaning in deviated wells.

5.2 Definitions of the various flow patterns

Because of the complexity of cuttings movements in a deviated annulus, some terms are required to describe the different flow phenomenon of the cuttings at different flow conditions. In this section the complex flow behaviours of drilled cuttings in a deviated wellbore are going to be characterised by flow patterns so that the minimum transport velocities can be easily defined. By doing so, we can not only follow the same standards of describing the complicated transport process, but also it is much easier for other researchers to compare the present results with their own. Further more, the minimum transport velocities can be easily determined based on the various specified flow patterns.

5.2.1 Homogeneous suspension

Cuttings are suspended and uniformly distributed over the annular space.

5.2.2 Heterogeneous suspension

Cuttings are suspended but there is a concentration gradient across the annulus with more cuttings in the lower-half of the annular space than that in the higher half of the annular space.
5.2.3 Suspension/saltation or Saltation/suspension

Cuttings are still in suspension but a lot of them are densely populated near the low-side wall so that they are virtually transported in the way of jumping forward or saltating on the surface of the low-side wall. If suspension is dominant, it is called “Suspension / Saltation”, and vice versa.

5.2.4 Cuttings clusters

Cuttings are suspended but they are transported in clusters and the cuttings inside the same cluster are travelling at roughly the same velocity.

5.2.5 Separated moving beds (dunes)

Separated cuttings beds are formed on the low-side wall of the annulus in this case. The cuttings on the surface of the beds travel forward whilst the cuttings inside the beds remain stationary so that the cuttings bed appears to roll or slide forward as a whole.

5.2.6 Continuous moving bed

A thin, continuous cuttings bed is formed on the low-side wall of the annulus with the cuttings near the low-side wall rolling or sliding forward at a lower transport velocity than those above them.

5.2.7 Stationary cuttings bed

A continuous cuttings bed is formed on the low-side wall of the annulus with the cuttings on the surface of the bed travelling whilst the cuttings inside the bed remain stationary.

5.3 Definitions of MTV for adequate hole cleaning

As discussed in the previous chapters, the philosophy of the present work is to determine the minimum transport velocity required to keep a borehole clean. The hole can only be cleaned completely if all the cuttings are moving upwards in the drill pipe/borehole annulus during circulation. In particular there must not be any static or downward moving cuttings in the borehole. In the present cuttings transport experiments, an attempt is made to
determine the minimum fluid velocity that will ensure that the above condition is satisfied. This velocity is defined as the MTV. In the experiments, two distinctly different mechanisms of cuttings transport have been identified, both of which satisfy the above requirement. Based on the definitions of the various flow patterns discussed in section 5.2, the minimum transport velocities for efficient hole cleaning can be easily defined.

5.3.1 MTV for cuttings rolling/sliding forward

This velocity is that at which the cuttings are rolling or sliding forward along the low-side wall of the annulus. Therefore, it corresponds to the minimum transport velocity in the flow pattern of separated moving beds (dunes) or continuous moving bed.

5.3.2 MTV for cuttings suspension

The minimum transport velocity for cuttings suspension should be at or above which all the cuttings can be suspended in the transport medium and transported upward together with the fluid. This velocity corresponds to the minimum transport velocity in the flow pattern of cuttings clusters or saltation/suspension.

5.3.3 MTV for vertical hole cleaning

In vertical wells, a cuttings bed will not be formed. The minimum transport velocity for hole cleaning has been determined as the velocity at or above which no cuttings will slide downward towards the hole bottom. Obviously this velocity is the MTV for cuttings suspension.

5.4 Depiction of the various flow patterns

The various flow patterns have been defined in section 5.2 and the MTV required for efficient hole cleaning has also been defined based on the various flow patterns. In this section the flow patterns are presented in a graphical form. Further more the two MTVs for adequate hole cleaning are also presented in graphics so that one can easily understand the different cuttings behaviours and hole cleaning situations at different mud pump rates.
5.4.1 Diagrammatic illustrations of the various flow patterns

The various flow patterns defined have been depicted in Fig. 5.4.1. From this figure the cuttings moving characteristics can be clearly understood.

5.4.2 Flow pattern map

According to the experimental data, a quantitative flow pattern map has been depicted in Fig. 5.4.2. It can be seen that in order to fully clean the hole, the fluid velocity has to be higher than the MTV for cuttings full suspension at hole angles of below 15° and the MTV for cuttings rolling when the hole angle is above 15° based on this specified set of experimental data.

The cuttings can only be fully transported up to the surface when the average fluid velocity is higher than either the line for cuttings moving bed or the line for cuttings suspension. If possible, it is suggested that the hole be cleaned using the velocity in the region marked “Suspension”. In this region all the cuttings are being transported in full suspension. In the region between the MTV for cuttings moving bed and cuttings suspension, some cuttings are transported in full suspension and some cuttings will settle on the low-side wall of the annulus and be transported in a moving bed.

However, when the fluid velocity is below the line for cuttings moving bed, some cuttings will settle on the low-side annular wall and become stationary or start sliding down, which should be avoided for the accumulation of the stationary cuttings or sliding down cuttings may cause stuck pipe, especially at high angle wells where the drill pipe has a strong tendency of offsetting towards the low-side annular wall.

It is a quite dangerous situation when the fluid velocity is below the line for cuttings sliding down. In this case the cuttings not only settle but will also start sliding down towards the hole bottom. This may easily cause stuck pipe.

In the present investigations efforts have been concentrated on the two curves plotted i.e. cuttings suspension and cuttings rolling/sliding. These two MTVs are used to investigate
Fig. 5.4.1 Diagrammatic illustration of the various flow patterns of cuttings transport
Fig. 5.4.2 Flow pattern map of drilled cuttings transport at various hole angles
how the drilling parameters may affect cuttings transport efficiency at different simulated drilling conditions.

5.5 Effects of the various drilling parameters on hole cleaning efficiency

From the above analysis, cuttings transport behaviours in deviated annuli have been well understood and the two MTVs required for adequate hole cleaning in deviated wells have been defined. For each set of experimental data, the MTV for cuttings rolling/sliding and the MTV for cuttings suspension are calculated and compiled. In this section the effects of the various drilling parameters on hole cleaning efficiency or on the two MTVs are analysed and presented based on the present experimental data. A summary of the experimental programme presented in the thesis is tabulated in Table 5.5.1.

Before proceeding for further discussions, it needs to be pointed out that during the current analysis, the MTV has been used for the measure of hole cleaning efficiency, in that the lower the MTV, the greater the fluid carrying capacity. It is clear that a higher MTV means that the fluid velocity required for hole cleaning is higher. Therefore the hole is more difficult to be cleaned and hole cleaning efficiency is lower for the given operational condition. Thus in the following analysis, it is assumed that the lower the MTV, the higher the hole cleaning efficiency. For example, if changing one parameter is increasing MTV, it means that changing this parameter is decreasing hole cleaning efficiency. Otherwise changing this parameter is increasing cuttings transport efficiency.

Based on this principle, the effects of the various drilling parameters on deviated hole cleaning are analysed using the present experimental data. It is easy to understand that during the present discussions if we say changing one parameter is favourable to deviated hole cleaning, this means changing this parameter will get a reduced MTV either by cuttings rolling or by cuttings suspension which will also be specified.

It also needs to be pointed out that the critical velocity described in the various figures is the fluid critical velocity for the transition from laminar to turbulent flow regime. If the fluid
Table 5.5.1 Summary of the cuttings transport experimental programme presented in the thesis

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Borehole geometry</th>
<th>Fluid Properties</th>
<th>Cuttings</th>
<th>Hole Angle (degrees)</th>
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<th>Serial No.</th>
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<th>Cuttings</th>
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Note: 1. R+: Experiments at the pipe axial rotary speed of 0, 60 and 120 rpm.
2. OR+: Experiments at the pipe orbital speed of 0, 60 and 120 rpm.
3. Borehole diameter is a constant of 13.7 cm.
4. d1: Outer diameter of the inner pipe; E%: Inner tube eccentricity; ds: Cuttings diameter; Cs%: Cuttings concentration by volume.
velocity is above the critical velocity, the fluid flow regime is turbulent. Otherwise, the fluid flow regime is laminar.

5.5.1 Effect of hole angle

Since it has been well known that deviated wellbores are more difficult to be cleaned than vertical wells, it may be easily speculated that hole angle is one of the most important parameters affecting cuttings transport during drilling operations. Hole angle has not only made cuttings transport become more difficult, it has also complicated the moving characteristics of drilled cuttings in the annulus as described in section 5.1. Thus, having a better understanding of the effects of hole angle on efficient hole cleaning is very important in the optimisation of directional drilling operations.

The effects of hole angle on MTV at different simulated drilling conditions are found to have the similar trend. In the present analysis, the effects of hole angle are mainly illustrated in the simplest geometrical configurations including large and small concentric annuli without drill pipe rotation. The similar trend for the effect of hole angle on the MTV can be found for other hole geometries, which are also discussed.

- Figs. 5.5.1 to 5.5.3 demonstrate a general trend that the MTV for cuttings rolling is very sensitive to hole angles. The MTV for cuttings rolling increases as hole angle increases from the vertical until 40° to 60° has been reached. Thereafter with a further increase in hole angle, the MTV will be reduced i.e. the hole is easier to be cleaned by cuttings rolling mechanism.

- A general trend for the effect of hole angle on the MTV for cuttings suspension can also be seen from Figs. 5.5.1 to 5.5.3. As hole angle increases, the MTV for cuttings suspension is increased shapely until reaching about 40° depending on the simulated drilling conditions. Thereafter the effect of hole angle on cuttings suspension is levelled out. A further increase in hole angle has little effect on the MTV. However the MTV may reach maximum at 60° to 75°. Then further increasing hole angle may get reduced MTVs i.e. a better hole cleaning situation. The worst transport hole angle i.e. the maximum MTV for cuttings suspension
usually falls from 60° to 75° though in some other cases the worst transport hole angle may fall out of the above stated range of hole angles. This is very interesting conclusion made during the present studies that it is not necessary horizontal hole angles which are most difficult to be cleaned even by cuttings suspension mechanism.

- It has been clearly shown that the MTV for vertical holes is much lower than that for high angle wells. This illustrates that deviated boreholes are more difficult to be cleaned than vertical wells.

- The MTV for cuttings suspension is always higher than that for cuttings rolling or sliding. However, for hole angles of 0 to 30 degrees, in most of the cases the cuttings either are being transported within the drilling fluids in full suspension or may start sliding downwards. No cuttings moving bed may be seen on the low-side wall of the annulus. This shows that in actual drilling practices cuttings suspension is dominant for hole cleaning at low hole angles and cuttings rolling or sliding may be the main transport mechanism for cuttings removal at high hole angles.

- The degree of the effect of hole angle on deviated hole cleaning is pipe eccentricity dependent. Comparing Figs. 5.5.3 and 5.5.4, it can be seen that for cuttings suspension, hole cleaning efficiency is more sensitive to hole angle at concentric annuli than that at highly eccentric annuli. That is, the effect of hole angle is more pronounced for concentric annuli than that for positive eccentric annuli. A similar trend can also be found for cuttings rolling.

- Angles from 40° to 60° from the vertical have been defined as the critical hole angles for the following reasons: a. A cuttings bed is not only formed but also it may slide downward if the fluid velocity is not high enough. b. At this range of hole angles, the maximum MTV occurred for cuttings rolling i.e. this range of hole angles are the most difficult hole angles to be cleaned. c. The sliding down cuttings bed is very dangerous situation in actual drilling practice because it may easily cause stuck pipe.
Fig. 5.5.1 Effect of hole angle on the MTV for both rolling and suspension (Fluid #4)

Test fluid: #4
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Inner pipe diameter: 8.89 cm
Critical velocity: 425.7 cm/s

Fig. 5.5.2 Effect of hole angle on the MTV for both rolling and suspension (Fluid #3)

Test fluid: #3
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Inner pipe diameter: 8.89 cm
Critical velocity: 228.6 cm/s

Fig. 5.5.3 Effect of hole angle on the MTV for both rolling and suspension (Big cuttings)

Test fluid: #4
Cuttings size: 2.8-3.35 mm
Cuttings concentration: 2%
Eccentricity: 0%
Inner pipe diameter: 6.10 cm
Critical velocity: 349.8 cm/s

Fig. 5.5.4 Effect of hole angle on the MTV for both rolling and suspension (+50% eccentric annulus)

Test fluid: #4
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: +50%
Inner pipe diameter: 6.10 cm
Critical velocity: 331.1 cm/s
5.5.2 Effect of fluid rheological properties

In rotary drilling operations drilled cuttings are transported up to the surface by the circulation of a drilling fluid. Fluid rheological properties are important in cuttings transport because it not only has great effect on hole cleaning efficiency but also it is one of the few adjustable parameters for improving cuttings transport during actual drilling operations. Viscosity and gel strength are also relevant in suspending cuttings when flow is stopped to make connections. Here the adjustable parameters mean that the parameters can be easily changed only for the purpose of improving hole cleaning. In fact, most of the affecting parameters can not be adjusted or controlled for the purpose of improving hole cleaning. For instance, hole angle is designed based on the overall drilling strategy and can not be changed only for the improvement of hole cleaning. Cuttings size and shape affect drilled cuttings transport but they can not be easily controlled in actual drilling practices.

Previous researchers have investigated the effects of fluid yield point, plastic viscosity and the YP/PV ratio on deviated hole cleaning. To investigate the effects of fluid rheological properties on cuttings transport efficiency, a variety of simulated drilling fluids have been used in the present study. Rather than simply using the n/K values, fluid rheograms are directly used for the analysis of fluid properties. Some special tests have also been conducted by step-wise viscosity reduction so that its effects on cuttings transport can be easily observed from the small changes of hole cleaning efficiency due to the viscosity reduction. It also needs to be pointed out that in order to simulate the effects of fluid viscosity more realistically, the test fluids have been engineered by the characterisation of actual drilling fluids from the North Sea. Therefore, the test fluids are representative of actual drilling fluids in rheology, which can be seen from Fig. 5.5.5. This figure shows that the test fluids have well covered the fluid rheological profiles of actual drilling fluids.

The effect of fluid rheology is strongly pipe rotary speed dependent. For simplicity, the effects of fluid properties on cuttings transport efficiency are analysed based on the experimental data in concentric and eccentric annuli, which has been shown from Figs. 5.5.6 to 5.5.20. Fig. 5.5.10 shows the seven different test fluids for the main cuttings
Fig. 5.5.5 Comparison of the rheogram of the test fluids and actual drilling fluids from the North Sea

Fig. 5.5.6 Effect of fluid rheology on the MTV for cuttings rolling (Fluid #4,3,1)

Fig. 5.5.7 Effect of fluid rheology on the MTV for cuttings suspension (Fluid #4,3,1)

Fig. 5.5.8 Effect of fluid rheology on the MTV for cuttings rolling (concentric annulus)
Fig. 5.5.9 Effect of fluid rheology on the MTV for cuttings suspension (concentric annulus)

Fig. 5.5.10 Rheogram of the test fluids for the effect of fluid rheology

Fig. 5.5.11 Rheogram of the fluids for the viscosity reduction experiments (Hole angle: 90 degrees)

Fig. 5.5.12 MTV for cuttings rolling at different viscosity reduction steps (Hole angle: 90 degrees)
Fig. 5.5.13 MTV for cuttings suspension at different viscosity reduction steps (Hole angle: 90 degrees)

Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Fig. 5.5.14 Rheogram of the fluids for the viscosity reduction experiments (Hole angle: 50 degrees)

Annular size: 13.7 x 6.1 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
- Visco1
- Visco2
- Visco3
- Visco4
- Visco5

Fig. 5.5.15 MTV for cuttings rolling at different viscosity reduction steps (Hole angle: 50 degrees)

Annular size: 13.7 x 6.1 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Fig. 5.5.16 MTV for cuttings suspension at different viscosity reduction steps (Hole angle: 50 degrees)
Fig. 5.5.17 Rheogram of the fluids for the viscosity reduction experiments (Hole angle: 0 degrees)

Fig. 5.5.18 MTV for cuttings suspension at different viscosity reduction steps (Hole angle: 0 degrees)

Fig. 5.5.19 Effect of fluid rheology on the MTV for cuttings rolling (+70% eccentricity)

Fig. 5.5.20 Effect of fluid rheology on the MTV for cuttings suspension (+70% eccentricity)
transport experiments in the present studies. Its effect at different pipe rotary speeds are discussed in section 5.5.4.

- From Figs. 5.5.6 and 5.5.7, it can be seen that for the small concentric annulus, fluid #4, which is the most viscous fluid among the three test fluids used (see Fig. 5.5.10 for their rheograms), provided the best hole cleaning (the lowest MTV for both cuttings rolling and cuttings suspension) and fluid #1 which is water only is advantageous to fluid #3 for deviated hole cleaning. However at vertical hole angles, an increase in fluid viscosity is always preferred for a better hole cleaning and water gave the worst cuttings transport.

- For the big annulus, a similar effect of fluid rheology on deviated hole cleaning efficiency can be found. A less viscous fluid #2 can provide a better cuttings transport than a more viscous fluid #3, which can be seen from Figs. 5.5.8 to 5.5.10. However, as the fluid viscosity is further increased, high viscosity fluid gives a better hole cleaning for both cuttings rolling and cuttings suspension mechanisms.

- Based on the experimental data, it is very clear that deviated wellbores can either be cleaned by low-viscous fluid in turbulent flow regime or by high-viscous fluid in laminar flow regime. For both cuttings rolling and cuttings suspension, the worst transport fluid has often been the medium viscous fluid in deviated wells (above 15°). However for vertical wells, high viscous polymer fluids usually result in reduced MTVs i.e. a better cuttings transport.

- From Figs. 5.5.11 through 5.5.18, a general trend holds true that as the fluid viscosity increases, the MTV for both cuttings rolling and cuttings suspension will be reduced. The above is true only if the fluid viscosity has been higher than the viscosity of the worst transport fluid.

- However, for highly eccentric annulus, low viscosity fluid will provide a better cuttings transport than high viscosity fluid, which can be seen from Figs. 5.5.19 and 5.5.20 for 70% eccentric annulus. Fluid #3 provided a better hole cleaning than fluid #4.
It needs to be pointed out that during the cuttings transport experiments it was observed that though high viscous fluid provided the best deviated hole cleaning in most of the cases, it takes much longer time for the high viscosity fluid to clean away a stationary cuttings bed once being formed on the low-side annular wall. This observation is very important in actual drilling practice which is discussed in detail in chapter 9.

In drilling operations, hole cleaning is not normally a problem for small hole sizes (8.5" or less) since either annular velocity or turbulence are options. The biggest problem is for larger holes (17.5" and 12.25") where annular velocity is not option and for most of the fluid types turbulence is not available. In this case, the optimisation of the fluid rheological properties are becoming even more important.

It should be mentioned that the present experiments address only the dynamic conditions. In actual drilling operations, circulation starts and stops on a regular basis due to the operation requirements (i.e. connections to drill string). When the circulation stops, cuttings settling can result. In this case, how to suspend the cuttings within the drilling fluid needs to be carefully considered.

5.5.3 Effect of cuttings size

As discussed in chapter 3, the only resistance force for the cuttings movement is the cuttings gravitational force, which is cubically proportional to the cuttings diameter. This indicates that cuttings size will play a very important role in deviated hole cleaning. The effects of cuttings size on deviated hole cleaning have been shown from Figs. 5.5.21 through 5.5.28. For convenience, cuttings in the size range of 1.7 - 2.0 mm are called small cuttings and those in the range of 2.8 - 3.35 mm are named as big cuttings. The following conclusions may be drawn from these experimental data:

- Generally speaking, small cuttings are easier to be transported out of the wellbore than big cuttings. This has been reflected from the lower MTV for both cuttings rolling and cuttings suspension for smaller cuttings, which has been shown from Figs. 5.5.21 to 5.5.24.
Fig. 5.5.21 Effect of cuttings size on the MTV for cuttings rolling (Fluid #6)

Test fluid: #6
Annular size: 13.7 x 6.1 cm
Cuttings Concentration: 2%
Rotary Speed: 0 rpm
Eccentricity: 0%

- ▲ Small Cuttings
- ○ Big Cuttings

Fig. 5.5.22 Effect of cuttings size on the MTV for cuttings suspension (Fluid #6)

Test fluid: #6
Annular size: 13.7 x 6.1 cm
Cuttings concentration: 2%
Rotary speed: 0 rpm
Eccentricity: 0%

- ▲ Small Cuttings
- ○ Big Cuttings

Fig. 5.5.23 Effect of cuttings size on the MTV for cuttings rolling (Fluid #1)

Test fluid: #1
Annular size: 13.7 x 8.89 cm
Pipe rotary speed: 0 rpm
Eccentricity: 0%
Critical velocity: 4.2 cm/s
Cuttings concentration: 2%

- ▲ Small cuttings
- ○ Big cuttings

Fig. 5.5.24 Effect of cuttings size on the MTV for cuttings suspension (Fluid #1)

Test fluid: #1
Annular size: 13.7 x 8.89 cm
Eccentricity: 0%
Pipe rotary speed: 0 rpm
Cuttings concentration: 2%
Critical velocity: 4.2 cm/s

- ▲ Small cuttings
- ○ Big cuttings
Fig. 5.5.25 Effect of cuttings size on the MTV for cuttings rolling (Fluid #3)

Test fluid: #3
- Annular size: 13.7 x 6.10 cm
- Eccentricity: 0%
- Rotary speed: 0 rpm
- Cuttings concentration: 2%
- Critical velocity: 179.2 cm/s

△ Small cuttings
○ Big cuttings

Fig. 5.5.26 Effect of cuttings size on the MTV for cuttings suspension (Fluid #3)

Test fluid: #3
- Annular size: 13.7 x 6.10 cm
- Eccentricity: 0%
- Rotary speed: 0 rpm
- Cuttings concentration: 2%
- Critical velocity: 179.2 cm/s

△ Small cuttings
○ Big cuttings

Fig. 5.5.27 Effect of cuttings size on the MTV for cuttings rolling (Fluid #4)

Test fluid: #4
- Annular size: 13.7 x 6.10 cm
- Pipe rotary speed: 0 rpm
- Eccentricity: 0%
- Cuttings concentration: 2%
- Critical velocity: 356.8 cm/s

△ Small cuttings
○ Big cuttings

Fig. 5.5.28 Effect of cuttings size on the MTV for cuttings suspension (Fluid #4)

Test fluid: #4
- Annular size: 13.7 x 6.10 cm
- Pipe rotary speed: 0 rpm
- Cuttings concentration: 2%
- Critical velocity: 356.8 cm/s

△ Small cuttings
○ Big cuttings
Fig. 5.5.29 Effect of pipe rotary speed on the MTV for cuttings rolling (Small annulus+Fluid #4)

Test fluid: #4
Annular size: 13.7 x 8.89 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Critical velocity: 425.7 cm/s
△ Rotary speed: 0 rpm
○ Rotary speed: 60 rpm

Fig. 5.5.30 Effect of pipe rotation on the MTV for cuttings suspension (Small annulus+Fluid #4)

Test fluid: #4
Annular size: 13.7 x 8.89 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
The critical velocity: 425.7 cm/s
△ Rotary speed: 0 rpm
○ Rotary speed: 60 rpm
● Rotary speed: 120 rpm

Fig. 5.5.31 Effect of pipe rotation on the MTV for cuttings rolling (Small annulus+Fluid #3)

Test fluid: #3
Annular size: 13.7 x 8.89 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Critical velocity: 228.6 cm/s
△ Rotary speed: 0 rpm
○ Rotary speed: 60 rpm
● Rotary speed: 120 rpm

Fig. 5.5.32 Effect of pipe rotation on the MTV for cuttings suspension (Small annulus+Fluid #3)

Test fluid: #3
Annular size: 13.7 x 8.89 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
The critical velocity: 228.6 cm/s
△ Rotary speed: 0 rpm
○ Rotary speed: 60 rpm
● Rotary speed: 120 rpm
Fig. 5.5.33 Effect of pipe rotation on the MTV for cuttings rolling (Small annulus+Fluid #1)

Test fluid: #1
Annular size: 13.7 x 8.89 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Critical velocity: 4.2 cm/s
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Fig. 5.5.34 Effect of pipe rotation on the MTV for cuttings suspension (Small annulus+Fluid #1)

Test fluid: #4
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Critical velocity: 356.78 cm/s
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Fig. 5.5.35 Effect of pipe rotation on the MTV for cuttings rolling (Big annulus+Fluid #4)

Fig. 5.5.36 Effect of pipe rotation on the MTV for cuttings suspension (Big annulus+Fluid #4)

Test fluid: #1
Annular size: 13.7 x 8.89 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Critical velocity: 4.2 cm/s
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Test fluid: #4
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Critical velocity: 356.8 cm/s
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm
Fig. 5.5.38 Effect of pipe rotation on the MTV for cuttings suspension (-50% eccentricity + Fluid #4)

Fig. 5.5.39 Effect of pipe rotation on the MTV for cuttings rolling (-50% eccentricity + Fluid #4)

Fig. 5.5.40 Effect of pipe rotation on the MTV for cuttings suspension (+50% eccentricity + Fluid #4)

Fig. 5.5.41 Effect of pipe rotation on the MTV for cuttings rolling (+50% eccentricity + Fluid #4)
Fig. 5.5.41 Effect of pipe rotation on the MTV for cuttings rolling (+70% eccentricity+Fluid #4)

Test fluid: #4
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: +70%
Critical velocity: 348.5 cm/s

- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Fig. 5.5.42 Effect of pipe rotation on the MTV for cuttings suspension (+70% eccentricity+Fluid #4)

Test fluid: #4
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: +70%
Critical velocity: 348.5 cm/s

- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm
effect at high rotary speed. At low pipe rotary speeds, pipe rotation has slight effect on cuttings suspension and has appreciable effect on cuttings rolling. When the drilling fluid is changed into #1 (water only), pipe rotation has no effect on hole cleaning efficiency at all hole angles though the same small annulus is still used, which has been demonstrated in Figs. 5.5.33 and 5.5.34. All the experimental data have fallen on the same line.

• When the small inner tube i.e. the big annulus is used, pipe rotation has slight or no effect at all at concentric annuli and -50% eccentric annuli where the drill pipe offsets toward the higher side wall of the annulus. This can be seen from Figs. 5.5.35 through 5.5.38. Increasing pipe rotation has little or no effect on cuttings transport even when relatively viscous fluid #4 is used.

• When the drill pipe offsets toward the low side wall of the annulus i.e. for positive eccentric annuli, pipe rotation will reduce the MTV for both cuttings rolling and cuttings suspension for viscous fluid. This has been shown from Figs. 5.5.39 through 5.5.42.

• Another important observation is that as the pipe rotary speed is increased, the cuttings moving velocity will also be increased. This is more significant when the flow pattern is cuttings moving bed. Pipe rotation can sweep away the cuttings on the low-side wall of the annulus towards the upper part of the annulus, which has a higher fluid point velocity. Thus, the cuttings can be removed at a higher velocity.

• As a summary, it is concluded that the effects of pipe rotation on deviated hole cleaning strongly depend upon the fluid viscosity and the annular clearance between the drill pipe and the low side wall of the annulus. As the annular clearance between the low side wall of the annulus and the drill pipe increases, the effect of the pipe rotation will be gradually reduced until reaching one point where the effect of drill pipe rotation will be diminished. Pipe rotation only has effects on cuttings transport when high viscous fluid is used. It will have no effect when water is used as the drilling fluid.
5.5.5 Effect of annular size

Annular size is referred to as the different combinations of variously sized drill pipes and wellbores. When the clearance between the drill pipe and wellbore is small, it is said to be a small annulus. Otherwise we call it a big annulus. During the present studies, three different annular sizes have been used including 13.7 cm x 8.89 cm, 13.7 cm x 6.10 cm and 13.7 cm x 3.34 cm, which are respectively called small annulus, big annulus and super annulus due to the different annular clearances. All the experimental results concerning the effect of annular size on deviated hole cleaning have been shown from Figs. 5.5.43 to 5.5.48.

- Figs. 5.5.43 and 5.5.48 showed that annular size has great effect on deviated hole cleaning no matter what fluids are used as the simulated drilling fluid. Better hole cleaning can be obtained in a small annulus than that in a big annulus because of the reduced MTV for both cuttings rolling and cuttings suspension.

In section 5.5.4, it has been known that pipe rotation can greatly improve deviated hole cleaning efficiency when small annuli are used. In this section, it is seen that a reduced MTV can be obtained for small annulus than that for big annulus even without pipe rotation. This, plus the fact that at the same flow rate the average fluid velocity is much higher for the small annulus than that for the big annulus, demonstrates that an increase in drill pipe size has great effect on deviated hole cleaning efficiency. As the drill pipe size increases, deviated hole cleaning can be greatly improved if the wellbore size is kept constant. A general guide is that highly deviated wells should be drilled with as large a drill pipe as possible. In the real world, the hole size varies due to hole enlargement etc., which should be taken into considerations during hole cleaning design.

5.5.6 Effect of pipe eccentricity

In deviated wells, drill pipe has a tendency to offset towards the low-side wall of the annulus. Here the high side refers to the case when the drill pipe offsets upwards towards the high side of the borehole wall and low side refers to the case when the drill pipe offsets
Fig. 5.5.43 Effect of annular size on the MTV for cuttings rolling (Fluid #4)

Test fluid: #4
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Pipe rotary speed: 0 rpm

- Annular size: 13.7 x 8.89 cm
  Critical velocity: 228.6 cm/s
- Annular size: 13.7 x 6.10 cm
  Critical velocity: 179.2 cm/s

Fig. 5.5.44 Effect of annular size on the MTV for cuttings suspension (Fluid #4)

Test fluid: #4
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Pipe rotary speed: 0 rpm

- Annular size: 13.7 x 8.89 cm
  Critical velo.: 425.7 cm/s
- Annular size: 13.7 x 6.10 cm
  Critical velo.: 356.8 cm/s

Fig. 5.5.45 Effect of annular size on the MTV for cuttings rolling (Fluid #3)

Test fluid: #3
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Pipe rotary speed: 0 rpm

- Annular size: 13.7 x 8.89 cm
  Critical velo.: 228.6 cm/s
- Annular size: 13.7 x 6.10 cm
  Critical velo.: 179.2 cm/s

Fig. 5.5.46 Effect of annular size on the MTV for cuttings suspension (Fluid #3)

Test fluid: #3
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Pipe rotary speed: 0 rpm

- Annular size: 13.7 x 8.89 cm
  Critical velo.: 228.6 cm/s
- Annular size: 13.7 x 6.10 cm
  Critical velo.: 179.2 cm/s
Fig. 5.5.47 Effect of annular size on the MTV for cuttings rolling (Fluid #2)

Test fluid: #2
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Pipe rotary speed: 0 rpm

- Annular size: 13.7 x 8.89 cm
  Critical velo.: 30.8 cm/s
- Annular size: 13.7 x 6.10 cm
  Critical velo.: 4.2 cm/s

Fig. 5.5.48 Effect of annular size on the MTV for cuttings suspension (Fluid #2)

Test fluid: #2
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: 0%
Pipe rotary speed: 0 rpm

- Annular size: 13.7 x 8.89 cm
  Critical velo.: 4.2 cm/s
- Annular size: 13.7 x 6.10 cm
  Critical velo.: 30.8 cm/s
downwards toward the low side wall of the wellbore. However, depending on the well path at a given moment some of the drill pipe will be low sided and some high sided. This is a dynamic situation and changes with depth. In rotary mode an element of corkscrewing will be present depending on the torque/drag acting on the drill pipe. Some of these items can be modelled. Wells are not necessarily shaped but can also be . In addition when viewed vertically azimuth can change simultaneously.

Therefore, to have a better understanding of drill pipe eccentricity on deviated hole cleaning is very important in directional drilling operations. During the present experimental investigations, five different levels of pipe eccentricity have been experimentally simulated, including 0%, 30%, 50%, -50%, and 70%. The effect of pipe eccentricity has been shown from Figs. 5.5.49 to 5.5.54.

- Figs. 5.5.49 and 5.5.50 illustrate that for both cuttings rolling and cuttings suspension, a general trend is that cuttings transport will become worse as the inner tube offsets towards the low side wall of the annulus. As the drill pipe offsets towards the higher side of the deviated annulus, the cuttings transport will be improved. Based on the experimental data, -50% eccentric annulus gave the lowest MTV for both cuttings rolling and cuttings suspension. Thus -50% eccentric annulus provided the best hole cleaning. The worst hole cleaning was obtained for 70% eccentric annulus. This is not favourable to the actual drilling practices where the drill pipe has the tendency of offsetting towards the low side wall of the annulus under the action of the gravitational force of the drill pipe itself or complement of the drill string.

- Figs. 5.5.51 and 5.5.52 show that for less viscous fluid #3, quite different phenomenon have been observed. The effect of pipe eccentricity is much more complicated. 50% provides the best cuttings transport and 0% eccentricity gives the worst cuttings transport for both cuttings rolling and cuttings suspension mechanisms. From the hole cleaning point of view, the following sequence of eccentricities which provided better cuttings transport is found in non-vertical
Fig. 5.5.49 Effect of pipe eccentricity on the MTV for cuttings rolling (Fluid #4)

Test fluid: #4
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Pipe rotary speed: 0 rpm
Critical velo.: 357.6 cm/s

△ Eccentricity: 0%
○ Eccentricity: +30%
■ Eccentricity: +50%
+ Eccentricity: +70%
△ Eccentricity: -50%

Fig. 5.5.50 Effect of pipe eccentricity on the MTV for cuttings suspension (Fluid #4)

Test fluid: #4
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Pipe rotary speed: 0 rpm
Critical velo.: 357.6 cm/s

△ Eccentricity: 0%
○ Eccentricity: +30%
■ Eccentricity: +50%
+ Eccentricity: +70%
△ Eccentricity: -50%

Fig. 5.5.51 Effect of pipe eccentricity on the MTV for cuttings rolling (Fluid #3)

Test fluid: #3
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Pipe rotary speed: 0 rpm
Critical velo.: 177.7 cm/s

△ Eccentricity: 0%
○ Eccentricity: +30%
■ Eccentricity: +50%
+ Eccentricity: +70%
△ Eccentricity: -50%

Fig. 5.5.52 Effect of pipe eccentricity on the MTV for cuttings suspension (Fluid #3)

Test fluid: #3
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Pipe rotary speed: 0 rpm
Critical velo.: 177.7 cm/s

△ Eccentricity: 0%
○ Eccentricity: +30%
■ Eccentricity: +50%
+ Eccentricity: +70%
△ Eccentricity: -50%
Fig. 5.5.53 Effect of pipe eccentricity on the MTV for cuttings rolling (Fluid #2)

Test fluid: #2
Annular size: 13.7 x 6.1 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Pipe rotary speed: 0 rpm
Critical velo.: 30.3 cm/s

- Eccentricity: 0%
- Eccentricity: +50%
- Eccentricity: -50%

Fig. 5.5.54 Effect of pipe eccentricity on the MTV for cuttings suspension (Fluid #2)

Test fluid: #2
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Pipe rotary speed: 0 rpm
Critical velocity: 30.3 cm/s

- Eccentricity: 0%
- Eccentricity: +30%
- Eccentricity: +50%
- Eccentricity: -50%
wells: 50%, 30%, 70%, -50% and concentric. This is true for both cuttings suspension and cuttings rolling.

- For even less viscous fluid #2, as shown in Figs. 5.5.53 and 5.5.54, 30% eccentric annulus gave the lowest MTV for both cuttings rolling and cuttings suspension and concentric annulus provided the highest MTV for both transport mechanisms. Therefore, 30% eccentric annulus gave the best hole cleaning and 0% provided the worst cuttings transport where the 70% eccentric annulus was not used.

- At vertical wells, no matter the fluid viscosity is high or low, a clear trend exists that as the drill pipe eccentricity increases, the MTV required for efficient cuttings transport is increasing. This trend is clearer for less viscous fluids #3 and #2. Except for the viscous fluid #4, concentric annulus always provides the best cuttings transport and 70% eccentric annulus always gives the worst cuttings transport. But for the viscous fluid #4, although the most difficult transport occurs at 70% eccentric annulus, the best transport condition is at 50% eccentric annulus but not at concentric annulus, which can be seen from Fig. 5.5.49. In vertical wells, concentric annulus gave the lowest MTV for cuttings suspension i.e. the best hole cleaning and 70% eccentric annulus provided the worst cuttings transport.

5.5.7 Effect of fluid flow regime

From the literature review it has been seen that fluid flow regime has important effect on drilled cuttings transport at various hole angles. However quite a confusion exists on how the flow regime may affect cuttings removal even in a vertical annulus which can be seen from Table 2.9.1.

In the present study, the critical fluid velocity for the transition from laminar to turbulent flow regime has been calculated based on the descriptions given in Appendix A7.2. It should be pointed out that in the calculation of the critical velocity it in fact assumes an uniform flow, which may not be the case. It also assumes that the existence of the cuttings and rotation of the drill pipe have no affects on the fluid flow regime. This critical velocity
has been shown in all the plots presented for the effects of drilling parameters on the MTV. If the MTV is higher than this critical velocity, the fluid flow regime is turbulent. Otherwise the flow regime is laminar. Now the effects of fluid flow regime on efficient hole cleaning are discussed based on some of the selected plots presented in the analysis so far.

- Generally speaking, for a concentric or a negative eccentric annulus, a deviated wellbore can be well cleaned either by high viscosity fluid in laminar flow or by low viscosity fluid or water in highly turbulent flow, which can be seen from Figs. 5.5.6 and 5.5.7. Fluid #1 (water only) in highly turbulent flow regime provided a better hole cleaning than the more viscous fluid #3 in laminar flow regime.

- When the drill pipe is offsetting towards the low side wall of the annulus, the effect of fluid flow regime will be changed. Low viscosity fluid can remove the drilled cuttings more efficiently than that the high viscosity fluid at all the hole angles investigated, which can be seen from Figs. 5.5.19 and 5.5.20 for 70% eccentric annulus.

Based on the above analysis, it may be concluded that the effect of fluid flow regime is strongly flow geometry dependent. Whether laminar flow will provide a better hole cleaning or turbulent flow will give a better cuttings transport depends on the specified operation situation.

### 5.5.8 Effect of cuttings concentration

Cuttings concentration or the rate of penetration will affect the overall load of cuttings in the drilling annulus. It will also affect the fluid effective viscosity field in the annulus. In fact, cuttings transport is a liquid/solid two phase flow problem. As one of the two phases, the amount of cuttings will affect hole cleaning efficiency. In the present experimental study, four different cuttings concentrations are used to simulate its effects on cuttings transport efficiency including 1%, 2%, 3% and 4% by volume. The effects of cuttings concentration have been shown from Figs. 5.5.55 through 5.5.58 and are discussed as follows:
Fig. 5.5.55 Effect of cuttings concentration on the MTV for cuttings rolling (Fluid #7)

Fig. 5.5.56 Effect of cuttings concentration on the MTV for cuttings suspension (Fluid #7)

Fig. 5.5.57 Effect of cuttings concentration on the MTV for cuttings rolling (Fluid #6)

Fig. 5.5.58 Effect of Cuttings concentration on the MTV for cuttings suspension (Fluid #6)
• An increase in cuttings concentration will result in an increase in the MTV for both cuttings rolling and cuttings suspension, which can be seen from Figs. 5.5.55 through 5.5.58. This indicates that as cuttings concentration increases, the MTV required for cuttings transport will be increased and hole cleaning efficiency will be reduced.

• Figs. 5.5.57 and 5.5.58 have clearly demonstrated that the most dramatic effects of cuttings concentration on the MTV for both cuttings rolling and cuttings suspension have been from 2% to 3%. It is interesting to note that for 1% and 2% cuttings concentrations, a little change of the MTV has been observed. The same results can be seen for 3% and 4% cuttings concentrations. However, as the cuttings concentration is changed from 2% to 3%, a significant increase of the MTV has been observed.

The above conclusions show that an increase in the rate of penetration will increase the MTV for hole cleaning i.e. decrease hole cleaning efficiency. Therefore, in order to maintain a better hole cleaning, some sacrifices on the rate of penetration is well justified.

5.5.9 Effect of drill pipe orbital motion

In drilling practices especially for highly deviated wells, the drill pipe has a tendency of offsetting towards the low-side annular wall. It can be easily imagined that the drill pipe may not only be rotated axially, but also may be rotated orbitally as well. The cuttings transport group at Heriot-watt University has conducted some experiments on the effects of drill pipe orbital motion on hole cleaning efficiency. In this section, some of the results are presented to show the significance of drill pipe orbital motion on cuttings transport efficiency. A comparison of the effect of orbital motion and the effect of axial rotation are also made for some specified experiments. In order to protect the simulator from being damaged during the experiments, the drill pipe is not allowed to sweeping freely. Instead, the drill pipe was controlled to a maximum eccentricity of 70% so that the drill pipe is not crashing the outer tube during the experiments.
It may also be pointed out that so far the effects of drill pipe orbital motion on deviated hole cleaning efficiency have only been studied by the drilled cuttings transport group in the Department of Petroleum Engineering, Heriot-Watt University. No similar investigation has been reported in the literature.

- Drill pipe orbital motion has significant effect on hole cleaning efficiency, especially for cuttings rolling, which can be clearly seen from Figs. 5.5.59 through 5.5.64.
- Figs. 5.5.59, 5.5.61 and 5.5.63 show that the effect of orbital motion is strongly fluid viscosity dependent. As the fluid viscosity decreases, the effect of orbital motion on the MTV for cuttings rolling is greatly decreased.
- A comparison of the effects of drill pipe rotation and orbital motion has been shown in Figs. 5.5.59, 5.5.65 and 5.5.67 for cuttings rolling and in Figs. 5.5.60, 5.5.66 and 5.5.68 for cuttings suspension. It can be seen that orbital motion is far more effective than axial drill pipe rotation from the view point of improving hole cleaning efficiency.

5.6 Summary

In the above discussion, the effects of the various drilling parameters on efficient cuttings transport have been analysed based on the present experimental data. It has been shown that the effects of the different drilling parameters on deviated hole cleaning are very complicated and are often interrelated. In actual drilling practices, a detailed analysis should first of all be carried out before modifying the operational conditions for a better hole cleaning. It should be noted that more detailed analysis and discussion of the effects of the different drilling parameters on deviated hole cleaning efficiency are presented in chapter 9.

In actual drilling practice, the detailed analysis of the effects of the drilling parameters is sometimes not practical. Therefore, to have some insights on the relative importance of the different drilling parameters on cuttings transport is very useful. In this section, the relative importance of the various drilling parameters on efficient hole cleaning is summarised in Table 5.6.1. From this table, it can be easily seen that the parameters which have strong effects on hole cleaning efficiency include fluid flow rate, hole angle, fluid rheology and
Fig. 5.5.63 Effect of orbital motion on the MTV for cuttings rolling (Fluid #7)

Test fluid: #7
Annular size: 13.7 x 6.10 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: about 70%
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Fig. 5.5.64 Effect of orbital motion on the MTV for cuttings suspension (Fluid #7)

Test fluid: #7
Annular size: 13.7 x 6.1 cm
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
Eccentricity: about 70%
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm
- Rotary speed: 120 rpm

Fig. 5.5.65 Effect of axial rotation on the MTV for cuttings rolling (Concentric annulus + Fluid #4)

Test fluid: #4
Annular size: 13.7 x 6.1 cm
Eccentricity: 0%
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
- Rotary speed: 0 rpm (Axial)
- Rotary speed: 60 rpm (Axial)
- Rotary speed: 120 rpm (Axial)

Fig. 5.5.66 Effect of axial rotation on the MTV for cuttings suspension (Concentric annulus + Fluid #4)

Test fluid: #4
Annular size: 13.7 x 6.1 cm
Eccentricity: 0%
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%
- Rotary speed: 0 rpm
- Rotary speed: 60 rpm (Axial)
- Rotary speed: 120 rpm (Axial)
Test fluid: #4
Annular size: 13.7 x 6.1 cm
Eccentricity: +70%
Cuttings concentration: 2%
Cuttings size: 1.7-2.0 mm

Fig. 5.5.67 Effect of axial rotary speed on the MTV for cuttings rolling (+70% eccentricity+Fluid #4)

Test fluid: #4
Annular size: 13.7 x 6.10 cm
Eccentricity: +70%
Cuttings size: 1.7-2.0 mm
Cuttings concentration: 2%

Fig. 5.5.68 Effect of axial rotary speed on the MTV for cuttings suspension (+70% eccentricity+Fluid #4)

- Rotary speed: 0rpm
- Rotary speed: 60rpm
- Rotary speed: 120rpm

*: Suspension not attained for 0 rpm at some angles
drill pipe orbital motion. The parameters which have moderate effects on hole cleaning efficiency are annular size, cuttings size, pipe eccentricity, fluid density, rate of penetration and fluid flow regime. The minor effects are from drill pipe axial rotary speed and fluid type.

It is obvious that fluid flow rate is the most important parameter to consider in actual drilling operations as long as hole cleaning is concerned. In order to clean the hole, the fluid velocity must be above a certain level. Otherwise, some of the cuttings may not be able to be cleaned. It has been concluded that deviated hole is more difficult to clean than vertical holes. As a matter of fact, hole angle has not only made cuttings transport become more difficult, it has also made the cuttings transport process become more complex as well. Fluid rheology and pipe orbital motion are also very important parameters affecting deviated hole cleaning efficiency. However, pipe axial rotation and fluid type are usually having little effect on cuttings transport efficiency. Therefore, their effects on hole cleaning have been ranked as minor. The rest of the other drilling parameters have moderate effects on hole cleaning efficiency based on the present experimental data.

Table 5.6.1 The relative importance of the drilling parameters on cuttings transport efficiency

<table>
<thead>
<tr>
<th>Drilling Parameters</th>
<th>Degree of the effect</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
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<tr>
<td>Flow rate</td>
<td></td>
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<tr>
<td>Hole angle</td>
<td></td>
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<tr>
<td>Fluid rheology</td>
<td></td>
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<tr>
<td>Pipe orbital motion</td>
<td>•</td>
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<td>Annular size</td>
<td></td>
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<tr>
<td>Cuttings size</td>
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<tr>
<td>Pipe eccentricity</td>
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</tr>
<tr>
<td>Fluid density</td>
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<tr>
<td>Rate of penetration</td>
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<tr>
<td>Fluid flow regime</td>
<td></td>
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<tr>
<td>Pipe axial rotation</td>
<td></td>
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<tr>
<td>Fluid type</td>
<td></td>
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</tbody>
</table>

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CHAPTER 6
LAMINAR FLOW OF HERSHEYEL-BULKLEY FLUIDS
THROUGH CONCENTRIC ANNULI

In chapter 5, it has been seen that the effects of the various drilling parameters on drilled cuttings transport are interrelated in a complicated manner. The effect of one parameter at one simulated drilling condition may be quite different from another. Analysis of the initiations of cuttings movement in a deviated wellbore has shown that fluid dynamic forces acting on the cuttings resting on the low side annular wall are the main forces to remove the cuttings there. The dynamic forces acting on the cuttings depend on many parameters including the fluid velocity profile and fluid viscosity profile adjacent to the particles. A better understanding of the fluid flow characteristics is quite important to the understanding of cuttings transport mechanics. Therefore, modelling of non-Newtonian annular flow is initiated for the generalised non-Newtonian fluids - Herschel-Bulkley fluids. In this chapter, the modelling results are presented. The theoretical studies are also substantiated by experimental data.

6.1 Previous studies

Modelling of annular flow of non-Newtonian fluids has been carried out by many researchers. In 1958 Fredrickson and Bird\(^{57}\) reported an extensive theoretical study on fluid flow of both power law and Bingham plastic fluids through concentric annuli. Thereafter their theoretical study was experimentally substantiated by Tiu and Bhattachryya\(^{65}\). Hanks and Larsen\(^{66}\) further modified the derivations by Fredrickson and Bird and a simple algebraic solution was obtained for the volumetric flow rate of a power law non-Newtonian fluid through concentric annuli in laminar flow. Though some other researchers\(^{67, 69-71}\) have also contributed to the modelling of non-Newtonian fluid flow, work was still limited for either power law fluid or Bingham plastic fluid. A recent
study was reported by Haciislamoglu\textsuperscript{(41)} on Herschel-Bulkley fluid flow through eccentric annuli. However because the unsheared plug was not fully defined, in the opinion of the present author, the solutions obtained is in error.

Modelling of the various flow equations for Herschel-Bulkley fluids has been carried out in the present study because of the following reasons:

- Herschel-Bulkley model can be used to effectively describe the fluid rheological properties.
- This model is a generalised form of the three commonly used fluid rheological models including Newtonian fluid, power law fluid and Bingham plastic fluid. The necessity of choosing a specified working rheological model for a specified job as in the past will be eliminated.

6.2 Basic assumptions

Flow of non-Newtonian fluids is complicated since these fluids are not only shear thinning, but also may be time-dependant. In the present study, the fluid is assumed to be:

- Incompressible;
- Inelastic;
- In steady state;
- Flowing in concentric annuli without pipe rotation;
- Time-independent (assuming no thixotropy);
- Isothermal;
- No-slip at all the solid boundaries (probably does occur since viscometers need to compensate for it);
- No end effects.

6.3 Derivation of the governing equation

In this section, the governing equation for fluid flow through various geometries is derived based on the equation of motion and the equation of continuity.
6.3.1 The equation of motion

In cylindrical co-ordinates, the equation of motion can be written as(63):

**r-component:**

\[
\rho \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} - \frac{v_z}{r} \frac{\partial v_r}{\partial z} = -\frac{\partial p}{\partial r} - \left( \frac{1}{r^2} \frac{\partial}{\partial r} \left( r \tau_r \right) + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} - \frac{\tau_{\theta\theta}}{r} + \frac{\partial \tau_{r\theta}}{\partial z} \right) + \rho g_r
\]

(6.3.1a)

**θ component:**

\[
\rho \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} + \frac{v_z}{r} \frac{\partial v_\theta}{\partial z} = -\frac{1}{r} \frac{\partial p}{\partial \theta} - \left( \frac{1}{r \theta} \frac{\partial}{\partial \theta} \left( r^2 \tau_\theta \right) + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{\partial \tau_{\theta\theta}}{\partial z} \right) + \rho g_\theta
\]

(6.3.1b)

**z component:**

\[
\rho \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} + \frac{v_z}{r} \frac{\partial v_z}{\partial z} = -\frac{\partial p}{\partial z} - \left( \frac{1}{r^2} \frac{\partial}{\partial r} \left( r \tau_z \right) + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{\partial \tau_{\theta\theta}}{\partial z} \right) + \rho g_z
\]

(6.3.1c)

6.3.2 The equation of continuity

The equation of continuity in a cylindrical co-ordinate system(63) may be written as:

\[
\frac{\partial p}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( \rho rv_r \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( \rho rv_\theta \right) + \frac{\partial}{\partial z} \left( \rho rv_z \right) = 0
\]

(6.3.2)

6.3.3 Governing equation for concentric annular flow

Based on the assumptions in section 6.2, the following simplifications can be made on the equation of motion and the equation of continuity:
a. The flow is in steady state. Then:
\[
\frac{\partial v_i}{\partial t} = 0 \quad i = r, \theta, z
\]  \hfill (6.3.3)

b. Since both inner tube and outer tube are stationary and the flow geometries are symmetrical to the axis, we can have:
\[
v_r = v_\theta = 0
\]  \hfill (6.3.4)

c. Because both \(v_\theta\) and \(v_r\) are equal to zero and the flow is time-independent, from the equation of continuity, we have:
\[
\frac{\partial v_z}{\partial z} = 0
\]  \hfill (6.3.5)

d. Because of the symmetrical geometry of annular flow, the fluid velocity will only change at \(r\) direction i.e.:
\[
\frac{\partial v_z}{\partial \theta} = 0
\]  \hfill (6.3.6)

e. From the flow equations, it can be further deduced that \(\tau_{\theta r}\) is the only non-zero shear stress, which is only a function of \(r\):
\[
\tau_{\theta r} = \tau(r)
\]  \hfill (6.3.7)

Based on the above simplifications, the following equation can be obtained from the equation of motion and the equation of continuity:
\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \tau_{r r} \right) = \rho_i g_z - \frac{\partial p}{\partial z}
\]  \hfill (6.3.8)

thus:
\[
\rho_i g_z - \frac{1}{r} \frac{\partial}{\partial r} \left( r \tau_{\theta r} \right) = 0
\]  \hfill (6.3.9)

Integrating Eq. 6.3.9, the governing equation for concentric annular flow without pipe rotation is obtained as:
\[ \frac{1}{2} g_r \cdot r^2 - r \cdot \tau_r = c \]  

(6.3.10)

where:

\[ \eta = \rho_d \frac{\partial \rho}{\partial z} \]  

(6.3.11)

and

\[ \frac{\partial \rho}{\partial z} = \frac{p_2 - p_1}{L} = -\frac{p_1 - p_2}{L} \]  

(6.3.12)

It has been seen that Eq. 6.3.10 was derived purely from the flow equations without any assumptions for the fluid rheological models. Therefore it can be used for both Newtonian fluids and non-Newtonian fluids.

### 6.4 Derivation of the various flow equations

In this section, laminar axial flow of Herschel-Bulkley fluids through concentric annuli is analysed and the various flow equations are derived, including the shear stress/shear rate profile, velocity profile, fluid viscosity profile and the relationship between fluid volumetric flow rate and the pressure drop. It needs to be pointed out that all the flow equations are derived for a fully developed laminar flow.

The various nomenclature used during the theoretical development is shown in Fig. 6.4.1. Using the nomenclature defined, the various flow equations can be represented in a simpler form. The several dimensionless parameters are given as follows:

\[ \lambda = \frac{r}{r_2}, \quad \lambda_- = \frac{r_-}{r_2}, \quad \lambda_+ = \frac{r_+}{r_2}, \quad \lambda_1 = \frac{r_1}{r_2} \]

#### 6.4.1 Width of the unsheared plug

For fluids with a non-zero yield point, there is always a unsheared plug in the middle of the annulus which will not be sheared by the fluid flow. Within the unsheared plug, the fluid velocity is uniform and the fluid shear stress is equal to the fluid yield point. Around the unsheared plug as shown in Fig. 6.4.1, the following relationship exists according to the principle of Shell Balance:
\[(2 \cdot \pi \cdot r_1 \cdot \tau_y + 2 \cdot \pi \cdot r_2 \cdot \tau_y) \cdot L = \pi \cdot (r_1^2 - r_2^2) \cdot g_p \cdot L \] (6.4.1)

Simplifying the above equation, we obtain:

\[w_p = r_+ - r_- = \frac{2.0 \cdot \tau_y}{g_p} \] (6.4.2)

The dimensionless width of the unsheared plug is expressed as:

\[\lambda_p = \frac{w_p}{r_2} = \lambda_+ - \lambda_- = \frac{2.0 \cdot \tau_y}{r_2 \cdot g_p} \] (6.4.3)

Eq. 6.4.3 shows that if \(\tau_y \neq 0.0\), \(\lambda_p\) will be greater than zero. The unsheared plug will always exist. Otherwise, there would be no unsheared plug, which is the case for both Newtonian fluids and power-law fluids.

![Velocity Profile](image)

Fig. 6.4.1 Illustration of concentric annular flow and its nomenclature for Herschel-Bulkley fluids

### 6.4.2 Shear stress profile

**a. General equations**

When \(\lambda_1 \leq \lambda \leq \lambda_2\), the fluid velocity increases as \(\lambda\) increases i.e. \(dv_{zz}/dr \geq 0.0\). Using the boundary condition of \(\tau_{zz} = -\tau_y\) at \(\lambda = \lambda_2\), the shear stress profile can be obtained from Eq. 6.3.10 while replacing \(2\tau_y/(r_2g_p)\) with \(\lambda_p\) in Eq. 6.4.3:
Similarly, for the boundary condition of $\tau_{zr} = \tau_y$ at $\lambda = \lambda_+$, we may obtain:

$$\tau_{zr} = \frac{1}{2} \cdot g_p \cdot r_2 \left( \left( \frac{\lambda^2}{\lambda} - \lambda \right) + \frac{\lambda_+ - \lambda_p}{\lambda} \right) \quad (\lambda_+ \leq \lambda \leq 1) \quad (6.4.5)$$

Eqs. 6.4.4 and 6.4.5 are the generalised shear stress profiles in a concentric annulus for Herschel-Bulkley fluids. From Eqs. 6.4.4 and 6.4.5, we can easily get the shear stresses acting on the outer wall of the inner tube and on the inner wall of the outer tube respectively as:

$$\tau_{zr} \big|_{\lambda = \lambda_i} = -\frac{1}{2} \cdot g_p \cdot r_2 \left( \left( \frac{\lambda^2}{\lambda} - \lambda_i \right) + \frac{\lambda_i - \lambda_p}{\lambda} \right) \quad (6.4.6)$$

$$\tau_{zr} \big|_{\lambda = 1} = \frac{1}{2} \cdot g_p \cdot r_2 \left( \left( 1 - \lambda^2 \right) + \lambda_+ \cdot \lambda_p \right) \quad (6.4.7)$$

Eqs. 6.4.6 and 6.4.7 demonstrate that the shear stress acting on the outer wall of the inner tube is not equal to that acting on the inner wall of the outer tube.

b. Discussion of some special cases

(1) For power-law fluids

If we set the yield stress $\tau_y$ equal to zero in both Eq. 6.4.4 and Eq. 6.4.5, then $\lambda_p$ is zero and $\lambda_-$ will be equal to $\lambda_0$. The shear stress profile for power law fluids can be obtained as:

$$\tau_{zr} = \frac{1}{2} \cdot g_p \cdot r_2 \left( \frac{\lambda^2}{\lambda} - \frac{\lambda_0}{\lambda} \right) \quad (6.4.8)$$

(2) For Bingham plastic fluids

If $n=1$, i.e. $s=1$, the fluid will become Bingham plastic fluid. In this case, the shear stress profile models will be the same as those for Herschel-Bulkley fluids. It can be seen from two previous studies(26, 57) that Eq. 6.4.4 and Eq. 6.4.5 are suitable for both power-law fluids and Bingham plastic fluids.
6.4.3 Shear rate profile

In Eq. 3.4.7a of section 3.4.1, "+" should be used when \( r_1 \leq r \leq r_2 \) with an increasing velocity profile and "-" should be used when \( r_+ \leq r \leq r_2 \) with a decreasing velocity profile. Substituting Eq. 6.4.4 and Eq. 6.4.5 into Eq. 3.4.7a, the fluid shear rate profiles are obtained as follows:

\[
\gamma = \frac{dv}{dr} = \left(\frac{g_p \cdot r_2}{2K}\right)^{\frac{1}{n}} \left[\left(\frac{\lambda_i}{\lambda} - 1\right) + \lambda_p \cdot \left(\frac{\lambda_i}{\lambda} - \lambda_\perp\right)\right]^n \quad (\lambda_i \leq \lambda \leq \lambda_\perp) \tag{6.4.9}
\]

and

\[
\gamma = \frac{dv}{dr} = -\left(\frac{g_p \cdot r_2}{2K}\right)^{\frac{1}{n}} \left[\left(\frac{\lambda}{\lambda} - 1\right) + \lambda_p \cdot \left(\frac{\lambda}{\lambda} - \lambda_\perp\right)\right]^n \quad (\lambda_+ \leq \lambda \leq 1) \tag{6.4.10}
\]

The shear rate acting on the inner and outer tube wall can be obtained separately as:

\[
\gamma|_{\lambda=\lambda_i} = \frac{dv}{dr}|_{\lambda=\lambda_i} = \left(\frac{g_p \cdot r_2}{2K}\right)^{\frac{1}{n}} \left[\left(\frac{\lambda_i}{\lambda_i} - 1\right) + \lambda_p \cdot \left(\frac{\lambda_i}{\lambda_i} - \lambda_\perp\right)\right]^n \tag{6.4.11}
\]

\[
\gamma|_{\lambda=1} = \frac{dv}{dr}|_{\lambda=1} = -\left(\frac{g_p \cdot r_2}{2K}\right)^{\frac{1}{n}} \left[\left(1 - \lambda_+\right) + \lambda_p \cdot \left(\lambda_+ - 1\right)\right]^n \tag{6.4.12}
\]

Using the same method as above, the shear rate profiles for both power law and Bingham plastic fluids can also be derived:

For power law fluids:

\[
\gamma = \frac{dv}{dr} = \pm \left(\frac{g_p \cdot r_2}{2K}\right)^{\frac{1}{n}} \left[\lambda_0 - \lambda\right]^n \tag{6.4.13}
\]

For Bingham plastic fluids:

\[
\gamma = \frac{dv}{dr} = \frac{g_p \cdot r_2}{2\mu_p} \left[\lambda_i - \lambda\right] + \lambda_p \cdot \left(\frac{\lambda_i}{\lambda} - 1\right) \quad (\lambda_i \leq \lambda \leq \lambda_\perp) \tag{6.4.14}
\]

and

\[
\gamma = \frac{dv}{dr} = -\frac{g_p \cdot r_2}{2\mu_p} \left[\lambda - \lambda_+\right] + \lambda_p \cdot \left(\frac{\lambda}{\lambda} - 1\right) \quad (\lambda_+ \leq \lambda \leq 1) \tag{6.4.15}
\]

These expressions are also exactly the same as the previous researchers\(^{(26,57)}\) for power law fluids and Bingham plastic fluids. This may also verify the present studies.
6.4.4 Fluid effective viscosity profile

Based on the definition of the effective viscosity, the viscosity profile can be obtained by dividing the fluid shear stress profile Eqs. 6.4.4 and 6.4.5 by the fluid shear rate profile Eqs. 6.4.9 and 6.4.10:

\[ \mu_e = \left( \frac{1}{2} \cdot g_p \cdot r_2 \right)^{1-s} \cdot K^s \cdot \frac{\left( \frac{\lambda^2}{\lambda} - \lambda \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} \right)}{\left( \frac{\lambda^2}{\lambda} - \lambda \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} - 1 \right)} \quad (\lambda_1 \leq \lambda < \lambda_+) \quad (6.4.16) \]

and

\[ \mu_e = \left( \frac{1}{2} \cdot g_p \cdot r_2 \right)^{1-s} \cdot K^s \cdot \frac{\left( \frac{\lambda - \lambda^2}{\lambda} \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} \right)}{\left( \frac{\lambda - \lambda^2}{\lambda} \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} - 1 \right)} \quad (\lambda_+ < \lambda \leq 1) \quad (6.4.17) \]

Within the unsheared plug ($\lambda_+ \leq \lambda \leq \lambda_+$), the fluid effective viscosity is infinite.

6.4.5 Fluid velocity profile

Integrating Eqs. 6.4.9 and 6.4.10 respectively, the fluid velocity profile can be obtained:

\[ v_z = \int_{\lambda_1}^{\lambda} \left( \frac{g_p}{2K} \right)^{1-s} \cdot \left( \frac{\lambda^2}{\lambda} - \lambda \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} - 1 \right) \, d\lambda \quad (\lambda_1 \leq \lambda \leq \lambda_+) \quad (6.4.18) \]

and

\[ v_z = \int_{\lambda_1}^{\lambda} \left( \frac{g_p}{2K} \right)^{1-s} \cdot \left( \lambda - \frac{\lambda^2}{\lambda} \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} - 1 \right) \, d\lambda \quad (\lambda_+ < \lambda \leq 1) \quad (6.4.19) \]

Substituting $\lambda = \lambda_+$ into Eq. 6.4.18 or $\lambda = \lambda_+$ into Eq. 6.4.19, the fluid velocity within the unsheared plug can be obtained as:

\[ v_{zo} = \int_{\lambda_1}^{\lambda} \left( \frac{g_p \cdot r_2}{2K} \right)^{1-s} \cdot \left( \frac{\lambda^2}{\lambda} - \lambda \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} - 1 \right) \, d\lambda \quad (6.4.20) \]

or
For power-law fluids, the fluid velocity profile will become:

\[ v_z = \int_{\lambda_1}^{\lambda_0} \left( \frac{g_p \cdot r_2}{2K} \right)^{\frac{1}{k}} \left( \frac{\lambda^2}{\lambda} - \lambda \right)^n d\lambda. \quad (\lambda_1 \leq \lambda \leq \lambda_0) \]  
\[ (6.4.22) \]

and

\[ v_z = \int_{\lambda_0}^{\lambda_1} \left( \frac{g_p \cdot r_2}{2K} \right)^{\frac{1}{k}} \left( \frac{\lambda^2}{\lambda} - \lambda \right)^n d\lambda. \quad (\lambda_0 \leq \lambda \leq 1) \]  
\[ (6.4.23) \]

For Bingham plastic fluids, the fluid velocity profile will become:

\[ v_z = \int_{\lambda_1}^{\lambda_0} \left( \frac{g_p \cdot r_2}{2K} \right)^{\frac{1}{k}} \left[ \frac{\lambda^2}{\lambda} - \lambda_0 + \lambda_p \cdot \left( \frac{\lambda_0}{\lambda} - 1 \right) \right] d\lambda. \quad (\lambda_1 \leq \lambda \leq \lambda_0) \]  
\[ (6.4.24) \]

and

\[ v_z = \int_{\lambda_0}^{\lambda_1} \left( \frac{g_p \cdot r_2}{2K} \right)^{\frac{1}{k}} \left[ \frac{\lambda^2}{\lambda} - \lambda_0 + \lambda_p \cdot \left( \frac{\lambda_0}{\lambda} - 1 \right) \right] d\lambda. \quad (\lambda_0 \leq \lambda \leq 1) \]  
\[ (6.4.25) \]

### 6.4.6 Volumetric flow rate and pressure gradient

The relationship between fluid volumetric flow rate and the pressure gradient is a very important aspect of annular flow characteristics. Based on the above discussions, the flow rate is expressed as:

\[ q = r_2 \int_{\lambda_1}^{\lambda_0} 2\pi \lambda v_z \, d\lambda + \pi \left( r_2^2 - r_1^2 \right) v_{z0} + r_2 \int_{\lambda_1}^{\lambda_0} 2\pi \lambda v_z \, d\lambda \]  
\[ (6.4.26) \]

Substituting Eqs. 6.4.18 and 6.4.19 into Eq. 6.4.26, the volumetric flow rate can be obtained as follows:

\[ q = r_2 \int_{\lambda_1}^{\lambda_0} 2\pi \lambda \left\{ \int_{\lambda_1}^{\lambda_0} \left( \frac{g_p \cdot r_2}{2K} \right)^{\frac{1}{k}} \left[ \frac{\lambda^2}{\lambda} - \lambda \right]^n d\lambda \right\} d\lambda + \pi \left( r_2^2 - r_1^2 \right) v_{z0} \]
\[ + r_2 \int_{\lambda_1}^{\lambda_0} 2\pi \lambda \left\{ \int_{\lambda_1}^{\lambda_0} \left( \frac{g_p \cdot r_2}{2K} \right)^{\frac{1}{k}} \left[ \frac{\lambda^2}{\lambda} - \lambda_0 + \lambda_p \cdot \left( \frac{\lambda_0}{\lambda} - 1 \right) \right]^n d\lambda \right\} d\lambda \]

i.e.: 
From the nature of the derived equations of fluid velocity profile and its volumetric flow rate, it is clear that analytical solutions could not be obtained. Because the various equations developed are crossly related with one another, only numerical solutions can be obtained by solving a group of simultaneous equations, which are discussed in the next section.

6.4.7 Solutions of the pressure gradient $g_p$ and the unsheared plug boundaries ($\lambda_+ & \lambda_-$)

All the flow equations for laminar axial flow of Herschel-Bulkley fluids through concentric annuli have been derived. From the derived equations it has been seen that all the equations are interrelated by the pressure gradient $g_p$ and the unsheared plug boundaries. In this section, the group of simultaneous equations are to be identified so as to solve the pressure gradient and the boundary conditions for a given flow rate, flow geometry and fluid rheological properties. They include the following equations:

a. Eq. 6.4.3 for the dimensionless width of the unsheared plug;

b. Substituting $\lambda_-$ and $\lambda_+$ into Eq. 6.4.20 and Eq. 6.4.21 respectively, two maximum velocities can be obtained, namely $v_{z+}$ and $v_{z-}$, which should be equal to $v_{z0}$. Based on the velocity profile, it may be known that $v_{z+} = v_{z-}$. Therefore a relationship between $\lambda_+$ and $\lambda_-$ is obtained as:

$$
\int_{\lambda_+}^{\lambda_-} \left( \frac{g_p \cdot r_2}{2K} \right)^i r_2 \left[ \left( \frac{\lambda_+^2}{\lambda} - \lambda \right) + \lambda_p \cdot \left( \frac{\lambda_+}{\lambda} - 1 \right) \right] d\lambda
= \int_{\lambda_-}^{\lambda_+} \left( \frac{g_p \cdot r_2}{2K} \right)^i r_2 \left[ \left( \frac{\lambda_-^2}{\lambda} - \lambda \right) + \lambda_p \cdot \left( \frac{\lambda_-}{\lambda} - 1 \right) \right] d\lambda
$$

(6.4.28)

c. Eq. 6.4.27 for the volumetric flow rate and pressure gradient.
As a summary of the above analysis, the simultaneous equations which need to be solved are as follows:

\[
\begin{align*}
\lambda_p &= \frac{2\tau_y}{r_2 \cdot g_p} \\
\lambda_p &= \lambda_+ - \lambda_- \\
\int_{\lambda_1}^{\lambda} \left( \frac{g_p \cdot r_2}{2K} \right)^2 r_1 \left[ \left( \frac{\lambda^2}{\lambda} - \lambda \right) + \lambda_p \cdot \left( \frac{\lambda}{\lambda} - 1 \right) \right] d\lambda \\
&= \int_{\lambda_1}^{\lambda} \left( \frac{g_p \cdot r_2}{2K} \right)^2 r_2 \left[ \lambda - \frac{\lambda^2}{\lambda} \right] + \lambda_p \cdot \left( \frac{\lambda}{\lambda} - 1 \right) \right] d\lambda \\
\end{align*}
\]

(6.4.29)

From the above four simultaneous equations it is seen that there are four unknown variables. Therefore it is very clear that the following four parameters can be solved from the equations, which include the pressure gradient \( g_p \), the dimensionless width of the unsheared plug \( \lambda_p \), the dimensionless boundaries \( \lambda_+ \) and \( \lambda_- \).

Substituting the above solutions into the various flow equations developed, the shear stress profile, shear rate profile, the effective viscosity profile and the velocity profile can be easily obtained respectively.

### 6.5 Sensitivity analysis of the various parameters on the flow profiles

A computer program has been developed to solve the flow equations derived for concentric annular flow of Herschel-Bulkley fluids. In this section a sensitivity analysis is carried out for the effects of the various parameters on the flow characteristics. The results are shown from Figs. 6.5.1 to 6.5.15. It needs to be pointed out that in the present analysis, only the fluid velocity profile, shear stress profile and the relationship between the volumetric flow rate and the pressure gradient are discussed.
Fig. 6.5.1 Effect of annular fluid velocity on pressure drop for concentric annuli

Fig. 6.5.2 Effect of average fluid velocity on the velocity profile inside a concentric annulus

Fig. 6.5.3 Effect of average fluid velocity on the shear stress profile inside a concentric annulus

Fig. 6.5.4 Effect of yield point on pressure drop in concentric annuli
Fig. 6.5.5 Effect of fluid yield stress on the velocity profile inside a concentric annulus

Fig. 6.5.6 Effect of fluid yield stress on the shear stress profile inside a concentric annulus

Fig. 6.5.7 Effect of annular size on pressure drop in concentric annuli

Fig. 6.5.8 Effect of annular size on the velocity profile inside a concentric annulus
Fig. 6.5.9 Effect of annular size on the shear stress profile inside a concentric annulus

Fig. 6.5.10 Effect of fluid consistency index on pressure drop in concentric annuli

Fig. 6.5.11 Effect of fluid consistency index on the velocity profile inside a concentric annulus

Fig. 6.5.12 Effect of fluid consistency index on the shear stress profile inside a concentric annulus
FLUID FLOW BEHAVIOUR INDEX: $n$

Fig. 6.5.13 Effect of fluid flow behaviour index on pressure drop in concentric annuli

RADIAL POSITION: $r/r_2$

Fig. 6.5.14 Effect of fluid behaviour index on the velocity profile inside a concentric annulus

RADIAL POSITION: $r/r_2$

Fig. 6.5.15 Effect of fluid behaviour index on the shear stress profile inside a concentric annulus
6.5.1 Average fluid velocity

The relationship between the pressure gradient and the average fluid velocity is shown in Fig. 6.5.1. It is interesting to note that an initial pressure gradient is required to make the fluid in motion for the fluids with a non-zero yield stress. Fig. 6.5.1 has also showed that as soon as the fluid is in motion (the average fluid velocity is approaching zero.), the pressure gradient is at a certain value, which is named as the minimum pressure gradient required to initiate the fluid flow and it is calculated based on the following equation:

\[
(g_p)_{\text{min}} = \frac{2.0 \cdot \tau_y}{r_2 - r_1} \tag{6.5.1}
\]

Eq. 6.5.1 demonstrates that the minimum pressure gradient required to initiate the fluid flow is depending on both the fluid yield point and the annular size. As the annular clearance increases, the minimum pressure gradient will be decreased i.e. an increase in annular clearance will make the fluid in motion easier. The fluid yield stress has the opposite effect on the minimum pressure gradient required to initiate the fluid flow. As the fluid yield stress increases, the minimum pressure gradient required to initiate the fluid flow will be increased.

From Fig. 6.5.1, it can be also seen that as the fluid velocity increases, the pressure drop will also be increased. The effects of the average annular fluid velocity on the fluid velocity profile and shear stress profile are shown in Figs. 6.5.2 and 6.5.3, which show that as the average fluid velocity increases, the fluid point velocity will be increased and so will the shear stress except for the shear stress within the unsheared plug. Because of the increased shear stress acting on the annular wall, this will increase the force acting on the cuttings within the annulus and this may improve cuttings transport efficiency accordingly.

6.5.2 Fluid yield point

The effects of fluid yield stress on the annular flow are shown from Figs. 6.5.4 through 6.5.6. Fig. 6.5.4 shows the annular pressure drop is linearly proportional to the fluid yield stress.
From Fig. 6.5.5 it can be seen that as the fluid yield point decreases, the width of the unsheared plug will be decreased, which will become zero for those fluids with a zero yield stress. The maximum fluid velocity will be reduced when the fluid yield point increases because of the increased unsheared plug. Fig. 6.5.6 demonstrates that the fluid shear stress will be increased with an increasing fluid yield point. For the fluid within the unsheared plug, the shear stress will be increased at the same increment of the yield point itself. From the cuttings transport point of view, it is clear that an increase in fluid yield point will increase the shear stress acting on the cuttings and this accordingly may improve cuttings transport.

6.5.3 Annular size

The effect of annular size on the pressure gradient is illustrated in Fig. 6.5.7. It can be seen that for the same outer tube diameter, as the inner tube size increases i.e. the annular clearance decreases, the pressure drop is increased.

Fig. 6.5.8 shows the velocity profiles for 8.5 x 5.0 in. & 12-1/4 x 5.0 in. annuli. The average fluid velocity and fluid properties used for these profiles are the same. It is very clear that the unsheared plug is wider for the bigger annulus. However, the maximum fluid velocity is higher for the smaller annulus. The shear stress profile at these two different sized annuli can be seen from Fig. 6.5.9. It is clear that except for the fluid within the unsheared plug, the shear stress for the smaller annulus is always higher than that in the bigger annulus. This may give a very good explanation to our experimental results on deviated hole cleaning efficiency. That is, at the same flow conditions, the smaller annulus will provide a better cuttings transport because of the greater shear stress acting on the cuttings inside the annulus.

6.5.4 Fluid consistency index K

The pressure drop is also linearly proportional to the fluid consistency index K. This is shown in Fig. 6.5.10. This effect is different from the effect of fluid yield point because the pressure gradient will be zero when the K value is equal to zero. That is, for a ideal zero viscous fluid there is no pressure loss in the flow system.
From Fig. 6.5.11 it is seen that as K value increases, the unsheared plug will become smaller. The maximum point velocity inside the annulus will be increased. Fig. 6.5.12 shows that as K value increases, the shear stress acting on the fluid will be greatly increased. However, the shear stress within the unsheared plug is the same. It is obvious that an increase in K value is favourable to cuttings transport for a fluid in laminar flow regime in a concentric annulus.

6.5.5 Fluid flow behaviour index n

As stated before, fluid behaviour index n is a description of the shear thinning characteristics and the deviation of the fluid away from Newtonian fluids. The effect of the flow behaviour index on the pressure drop has been shown in Fig. 6.5.13. As expected, as n decreases, the pressure drop will be decreased and vice versa. From Fig. 6.5.14, it is clear that as n value increases, the fluid velocity profile will become sharper and the unsheared plug of the fluid will be reduced. The effect of fluid behaviour index on the shear stress profile has been shown in Fig. 6.5.15. A very clear trend is that as n value increases, the shear stress acting on the fluid will be greatly increased. Thus, a higher n value is good for cuttings transport while keeping all the other parameters constant.

6.6 Comparison with the previous studies

The various flow equations for concentric annular flow of Herschel-Bulkley fluids have been theoretically derived. For the special cases i.e. power law and Bingham plastic fluid, the equations have been compared against the derivations from Fredrickson and Bird (57). In this section, two examples listed in the above paper are calculated using the present models. The results are tabulated in Table 6.6.1 together with the other authors' predictions. From this table, it can be seen that an excellent agreement is obtained between Fredrickson and Bird' and the present studies.
Table 6.6.1 Comparison of the annular pressure drops between Fredrickson and Bird' and the present studies (In c.g.s Units)

| Example 1                      | + | Example 2                      |
|--------------------------------+---+--------------------------------|
| **Power-law fluid**            | + | **Bingham plastic fluid**      |
| Average velocity: 152.4         | + | Average velocity: 152.4        |
| $n=0.7153$                      | + | $\tau_y=265.2552$              |
| $K=6.04038$                     | + | $\mu_p=0.27866$                |
| Annular size: 5.260848 x 2.1359043 | + | Annular size: 5.25018 x 2.1336 |

<table>
<thead>
<tr>
<th>$g_p$</th>
<th>$g_p$</th>
<th>$g_p$</th>
<th>$g_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F &amp; B'</td>
<td>Present Study</td>
<td>F &amp; B'</td>
<td>Present Study</td>
</tr>
<tr>
<td>400.571</td>
<td>399.9048</td>
<td>686.33</td>
<td>671.6477</td>
</tr>
</tbody>
</table>

Difference: 0.17%             + Difference: 1.71%

Note: F & B' = Fredrickson and Bird' studies

6.7 Experimental verification of the present studies

In order to experimentally verify the theoretical derivations of the various flow equations, annular flow experiments have been carried out using the flow loop described in chapter 4. In this section, the experimental results are summarised and presented. The results showed a very good agreement with the present theoretical predictions.

6.7.1 Experimental facilities

The experimental facilities used for the annular flow experiments are the same as that described in chapter 4. The experiments have been conducted only in concentric annuli without pipe rotation with different inner tube sizes.

6.7.2 Experimental procedures

The annular flow experiments are being conducted following the procedures outlined below:
a. The fluid with the desired rheological properties is firstly mixed in the two mixing tanks. After completing the mixing, the fluid is left overnight so that the air bubbles trapped within the fluid could be fully released.

b. Before starting the experiments, the fluid was pre-sheared for about 20 minutes so as to get the fluid fully sheared and the fluid rheological properties stabilised.

c. Starting the pump at maximum flow rate. After the fluid flow has reached steady state, recording the pressure drop and the fluid flow rate. In order to get accurate data, both the flow rate and the pressure drop have been recorded by a BBC Logger which can take all the readings simultaneously for a given time period. The final readings will be taken by averaging the recordings.

d. Decrease the fluid flow rate and repeat step c above until the minimum flow rate has been reached. Then increasing the flow rate to retake all the readings so as to check the repeatability of the experimental data.

e. Before and after the experiments, some fluid samples were taken and the corresponding temperatures were recorded.

f. After the experiments, the rheological properties of fluid samples were measured by Fann VG, HAAKE and Brookfield viscometers.

6.7.3 Comparison between the experimental data and the theoretical predictions

It is understood that the easiest way to substantiate the modelling of fluid flow is to check the pressure gradient under the given flow conditions. Therefore during the present investigations, comparison is made between the measured pressure gradient and the predicted pressure gradient and excellent agreement has been obtained. These results have been shown from Figs. 6.7.1 to 6.7.5 for the pressure drop of Herschel-Bulkley fluids through concentric annuli.

Figs. 6.7.1 and 6.7.2 have showed the comparison in the smaller annulus for a zero yield polymer fluid i.e. power law fluids. Experiments conducted in a big annulus with a zero yield fluid has been illustrated in Fig. 6.7.3. The three figures showed that for the special
Fig. 6.7.1 Measured pressure drop against theoretical predictions for Herschel-Bulkley fluids through a concentric annulus

Fig. 6.7.2 Measured pressure drop against theoretical predictions for Herschel-Bulkley fluid through a concentric annulus

Fig. 6.7.3 Measured pressure drop against theoretical predictions for Herschel-Bulkley fluid through a concentric annulus

Fig. 6.7.4 Measured pressure drop against theoretical predictions for Herschel-Bulkley fluid through a concentric annulus
Fig. 6.7.5 Measured pressure drop against theoretical predictions for Herschel-Bulkley through a concentric annulus
case of power law fluids, the present theoretical derivations have showed an excellent agreement with the experimental data.

From Fig. 6.7.4, it can be seen that an excellent agreement has also been obtained between the experimental data and the theoretical predictions for a non-zero Herschel-Bulkley fluid. For another special case of Bingham plastic fluid (n=1.0), a good agreement has also been obtained, which can be seen from Fig. 6.7.5.

The above analysis has showed that the theoretical derivations for Herschel-Bulkley fluids are correct and they can be used for the special cases of power law and Bingham plastic fluid as well. The comparison between the model predictions and the experimental data has verified that the various models derived are valid and can be used with confidence.
It is known that drilling fluids are shear thinning non-Newtonian fluids, whose viscosity decreases as the shear rate acting on the fluid increases. Due to the dependence of cuttings settling velocity on the fluid viscosity, cuttings settling velocity in static drilling fluids can be significantly different from that in dynamic ones because of the additional shear imposed by fluid flow. However, because of the complexities involved, no valid technique was used to experimentally measure cuttings settling velocity in dynamic fluids. In this chapter, a new technique is proposed to experimentally study cuttings settling velocity under actual flow conditions. Taking the experimental data as basis, a new model is developed for cuttings settling velocity in dynamic non-Newtonian fluids. This model has been used for the predictions of MTV required for adequate vertical hole cleaning. Finally, a brief discussion is presented on why the previous researchers have made different conclusions for efficient cuttings transport in vertical wells (See Table 2.9.1).

7.1 Previous studies

In section 2.2.3, it has been concluded that the measurements of cuttings settling velocity in dynamic flow conditions can only be obtained by taking the following readings simultaneously:

- Cuttings transport velocity;
- The exact location of the cuttings in the annulus;
- The fluid velocity profile across the annulus.

From the review of the previous studies on cuttings settling in non-Newtonian drilling fluids, it has been concluded that no valid experimental data are available for cuttings
settling in dynamic non-Newtonian drilling fluids. In the following discussions, some of
the experimental techniques for proppant transport in dynamic non-Newtonian fracturing
fluids are analysed. The theoretical considerations of the effective viscosity of non-
Newtonian fluids around a settling particle are also discussed.

7.1.1 Experimental studies on proppant transport in dynamic non-
Newtonian fracturing fluids

Though no valid experimental techniques were available for the measurement of cuttings
settling velocity in dynamic non-Newtonian drilling fluids, some good attempts(76, 78, 79 &
75) were made for proppant transport through non-Newtonian fracturing fluids.

Novonty(78) reported his experimental investigation into particle settling through both
Newtonian and non-Newtonian fluids under “dynamic” conditions. The dynamic effect
was simulated using a concentric annulus with a rotating inner tube. The annulus is
composed of concentric cylinders approximately 1 ft in diameter and 3 ft high. The annular
gap between the two cylinders was varied from 1/4” to 3/4”. For the specified geometry,
the shear rate imposed on the fluid by the rotating inner tube was regarded as constant
across the annular gap for a given inner tube rotary speed. According to this study, the
following conclusions were made:

- Stokes' law was not valid for the dynamic proppant settling velocity data.
- In Newtonian fluids, inner tube rotation did not affect the settling velocity of the
  proppant. However, in highly non-Newtonian fluids (0.34<n<0.40), proppants
  settled much faster when the fluid was being sheared. For the smallest particles,
  there was a 40-fold increase in settling velocity when the shear rate imposed on
  the fluid was increased from 0 to 90/sec. For the largest particles, this effect was
  only about 6-fold.
- Proppants which were completely suspended in a stagnant, highly non-
  Newtonian fluid settled when the fluid was sheared.
- In summary, settling velocities measured in stagnant non-Newtonian fluids are
  not reliable for predicting proppant transport in actual flow conditions. Settling
velocity must be determined as a function of the fluid shear rate, which includes both the shear rate imposed by fluid motion and the shear rate due to particle settling.

Though Novonty made a great effort, several arguments may be raised:

- The simulated “dynamic flow” is not realistic. In actual practices, the fluid is being circulated through the annulus. However, Novonty simulated the “dynamic flow” by rotating the inner tube.
- The assumption that the shear rate imposed on the fluid by inner tube rotation is constant across the annulus is not valid.
- During the experiments, the particle may not settle along a straight line and its exact location may be very difficult to follow and be recorded.

In 1981, another paper was published by Hannah and Harrington(79), using a similar experimental rig to Novonty(78). However, instead of rotating the inner tube, the shear rate was simulated by a rotating outer tube. The shear rate imposed on the fluid by outer tube rotation was regarded to be varied across the annulus. An equation was reported for the radial position versus the fluid shear rate at different outer tube rotary speeds. Some models were used to determine the radial position of the particle against the change of particle rotary speed (rpm).

Because of the highly viscous fluids used, the vertical shear rate by particle settling $v_s/d_s$ was regarded to be small relative to the shear rate by fluid flow and its effect was ignored during the theoretical correlation. The experimental procedures are as follows:

- Simultaneous measurements of particle rpm (rotary speed) and settling velocity;
- Use of the particle rpm to find the location of the particle in the annular gap;
- Calculation of the shear rate imposed upon the fluid at the location of the particle.

It was concluded that using the fluid shear rate imposed by fluid motion, particle settling velocity under dynamic conditions can be calculated using Stokes Law. However using $v_s/d_s$ to represent the shear rate for static particle settling, the particle settling velocities
predicted by Stokes' Law were some 20 to 60 times lower than the experimental data obtained in dynamic conditions.

Except for the unrealistically simulated "dynamic" flow, the following point is found difficult to be understood by the present author:

- How the equation of particle rpm versus particle position can be derived and accurately measured during the experiments.

A year later, Shah(76) reported another interesting paper. The experimental rig used was a vertical column, which has a geometry of 2.5" in diameter x 7' long. The fluid was circulated by a Moyno pump for dynamic particle settling velocity measurements. During the experiments, the flow rate at which the particle can be maintained stationary at a desired point in the column was used for the calculation of the proppant settling velocity. In order to prevent the immigration of particles towards the pipe wall, a fine, stainless steel wire [diameter=0.013"] was centred axially in the column and held under tension. Solid particles with a small hole [diameter=0.043"] drilled in the centre were threaded on the stainless steel wire. Fluid flow forced the particle to move vertically along the wire. The diameter of the particles used in the experiments ranged from 0.04" to 0.4" with specific gravity from 1.05 to 11.0. Materials used included plastic, glass, aluminium, Teflon polymer, brass, sapphire, steel, and lead.

The test procedure for particle settling under dynamic flow condition is that the column was filled with the test fluid. The particle was released and flow rate was adjusted to keep the particle "stationary". For such experiments, the centre-line velocity in the tube was used as the particle settling velocity. For Newtonian fluids, the maximum fluid velocity in the central region of the column \(v_m\) is regarded to be twice of the average fluid velocity \(v_f\):

\[
v_m = 2.0 \cdot v_f
\]  

(7.1.1)

For non-Newtonian fluids, the maximum fluid velocity in the column is less than twice of the average velocity and was taken as a function of \(n\), the fluid behaviour index:
\[ v_m = \left( \frac{3n+1}{n+1} \right) v_f \]  

(7.1.2)

As the particle Reynolds number is increased beyond the range of Stokes' law, eddies form immediately downstream of the particle so that the maximum fluid velocity across the column can not be calculated using the above two equations. The fluid velocity to maintain the particle at a desired point in the tube may be somewhere between \( v_m \) and \( v_f \). It has been proved in the past that the fluid velocity profile for turbulent non-Newtonian fluids is substantially the same as that for Newtonian fluids. In this case, the maximum fluid velocity either for Newtonian or for non-Newtonian fluids is 1.25 times the average fluid velocity. In absence of a better relationship, when \( N_{Re_p} > 1.0 \), \( v_m \) was calculated by:

\[ v_m = 1.25 \cdot v_f \]  

(7.1.3)

It was concluded that dynamic settling velocity data agreed reasonably well with the correlations developed from static settling velocity data. Thus, the shear rate imposed by fluid circulation was not considered in the model correlation.

A big improvement of Hanah's experiments is that the particle was axially controlled within the central region of the pipe by a wire-line so that the maximum fluid velocity in the pipe can be taken as the particle settling velocity when the particle was kept stationary at a well adjusted flow rate. However, there are still several points to be discussed:

- The purposely set guiding wire may restrict the movements of the particles.
- A hole was drilled through the particle, which may change the flow field around it and affect the quality of the experimental data.
- The measuring point was chosen as the centre-line of the pipe, where the shear rate by fluid motion is in fact zero. This may be one of the reasons why it was concluded that dynamic settling velocity data agreed reasonably well with the correlations developed from static settling velocity data.

The above analysis showed that the various techniques for the measurements of proppant settling velocity in dynamic fracturing non-Newtonian fluids are far from satisfactory. However, the results have indicated that particle settling velocity in static non-Newtonian fluids may be significantly different from that in dynamic ones!
7.1.2 Theoretical studies on the effective viscosity of non-Newtonian fluids around a settling particle

In the theoretical modelling of particle settling velocity in non-Newtonian fluids, the most important aspect has been the consideration of the effective viscosity of the fluid around the settling particle. For the different fluid rheological models, the fluid effective viscosity, which is defined as the ratio of the shear stress to the shear rate imposed on the fluid, may be expressed as follows:

For power law fluids:

\[ \mu_e = K \cdot (\gamma)^{(n-1)} \]  
(3.4.4)

For Bingham plastic fluids:

\[ \mu_e = \frac{\tau_y}{\gamma} + \mu_p \]  
(3.4.6)

And for Herschel-Bulkley fluids:

\[ \mu_e = \frac{\tau_y}{\gamma} + K \cdot (\gamma)^{(n-1)} \]  
(3.4.8)

The above equations show that fluid effective viscosity is decreasing as the shear rate imposed on the fluid is increased. The varying fluid viscosity has made the modelling of particle settling velocity in non-Newtonian fluids much more difficult than that in Newtonian ones due to the fact that in non-Newtonian fluids, the shear rate imposed by a settling particle itself will affect its settling velocity.

In actual drilling practices, the cuttings are settling in a non-Newtonian fluid while the fluid is being circulated. It is obvious that both the cuttings settling and fluid circulation will change the fluid viscosity field around the cuttings. In this section, the various theoretical treatments for the effective viscosity of non-Newtonian fluids around the settling particle are discussed.

a. Constant fluid viscosity

Drilling fluids are non-Newtonian in rheological properties. Therefore, if the varying viscosity of the non-Newtonian fluids is treated as a constant, this treatment would fail to
reveal the true viscosity of the fluid. Because of this fact, as far as we know, only Hopkin\(^4\) has directly correlated the relationship between the funnel viscosity and particle settling velocity, and the relationship between the Bingham yield value and the particle settling velocity. Obviously the usefulness of these models is extremely limited.

b. Viscosity field by cuttings settling

It is easy to understand that a settling particle will change the fluid shear field around it, which obviously will affect the fluid effective viscosity around the particles and consequently will affect the particle settling velocity in a non-Newtonian fluid. The effect of particle settling velocity on the fluid effective viscosity has been considered using the shear rate imposed on the fluid by the settling particle itself. Thereafter, the effective viscosity around the settling particle can be calculated using Eq. 3.4.4, 3.4.6 or 3.4.8 depending on the fluid rheological models used.

Novonty\(^78\) suggested that the effective shear rate imposed on the fluid by a settling proppant in non-Newtonian fracturing fluids should be calculated by \(v_s/d_s\), which was also adopted by Peden and Luo\(^18\) for particle settling in power law fluids:

\[
\gamma_{sp} = \frac{v_s}{d_s} \quad (7.1.4)
\]

However Daneshy\(^77\) suggested using \(3(v_s/d_s)\) rather than \(v_s/d_s\) to calculate the effective shear rate imposed on the fluid by a settling particle:

\[
\gamma_{sp} = 3 \cdot \frac{v_s}{d_s} \quad (7.1.5)
\]

which was supported by Shah\(^76\) after an experimental investigation into proppant settling in non-Newtonian fracturing fluids under both static and dynamic conditions.

Zeidler\(^6\) proposed an equivalent viscosity that a Newtonian fluid would have in order to yield the same settling velocity as that of the particle in a non-Newtonian fluid. Based on his experimental data, an empirical equation was developed for the equivalent shear rate surrounding a settling particle, which is expressed as:
\[ \gamma_{eq} = \frac{v_s}{d_{des}} \cdot \frac{1-n}{2} \left( \frac{d_{side}}{d_{si}} \right)^{(n+5)(1.1-0.98(1-n^2)^{0.5})} \]  
(7.1.6)

Walker and Mayes\(^{(9)}\) developed an empirical relation for the shear stress caused by a circular disk in flatwise settling, which was given by:

\[ \tau_s = 68.95 [h_s (\rho_s - \rho_f)]^{1/2} \]  
(7.1.7)

The shear rate \( \gamma_s \), corresponding to the shear stress \( \tau_s \), is determined by a smooth plot of Fann viscometer dial readings against the shear rates. The fluid effective viscosity is then calculated by:

\[ \mu_e = \frac{\tau_s}{\gamma_s} \]  
(3.4.3)

It needs to be pointed out that except for Novonty\(^{(78)}\), all the above researchers have taken the effective shear rate by particle settling as the effective shear rate imposed on the fluid around the settling particles. The effect of fluid viscosity due to fluid circulation was not considered.

c. Effective viscosity due to fluid motion

Moore\(^{(11)}\) modified the settling velocity model for cuttings settling in static non-Newtonian fluids so that it could be used for cuttings settling in dynamic fluids for the average flowing conditions experienced by the cuttings during drilling operations. For power law fluids, the effective viscosity for particle settling in dynamic fluids is calculated as the equivalent Newtonian viscosity using the method proposed by Dodge and Metzner\(^{(82)}\) for annular pressure gradient calculations, which was reported as:

\[ \mu_e = \frac{K}{144} \left( \frac{11.997 \cdot (d_2 - d_1)}{\nu_f} \right)^{1-n} \left( \frac{2.0 + \frac{1.0}{n}}{0.0208} \right)^n \]  
(7.1.8)

The correlation by Moore\(^{(11)}\) predicts that particle settling velocity is independent of annular fluid velocity in turbulent flow regime. For the transition and laminar flow regimes, however, particle settling velocity is predicted to increase as annular fluid velocity increases. Moore's model in fact considered the fluid viscosity close to the wall region of
the annulus, which may not reflect the fluid viscosity field experienced by most cuttings in the annulus.

Chien(5) suggested that in turbulent flow regime, the Bingham plastic viscosity, $\mu_p$, could be used as the equivalent viscosity for particle settling. However, for highly viscous polymer type drilling fluids, the effective viscosity for Bingham plastic fluids is calculated by the following empirical equation, which is based on the procedure by Skelland(83):

$$\mu_e = \mu_p + \frac{\tau_y \cdot d}{6 \cdot \nu_f} \tag{7.1.9}$$

It was pointed out that preliminary experimental data using rotameter as test sections showed that the fluid effective viscosity the cuttings experienced was greater than the plastic viscosity of the drilling fluid at all velocities tested, and the difference decreased as the fluid velocity was increased. It was also concluded that particle settling velocity was independent of the fluid velocity for turbulent flow. For the case of very viscous polymer-type drilling fluids, the settling velocity was increased by an increase in annular fluid velocity.

Zeidler(8) concluded that the fluid effective viscosity for cuttings settling in dynamic non-Newtonian fluids should be the fluid viscosity at the annular wall. Therefore the effective viscosity around the settling particles was calculated based on the method proposed by Fredrickson and Bird(57).

Hall et al.(2) have also concluded that annular fluid velocity would affect the cuttings settling velocity in the annulus. Walker and Kory(81) discussed the use of an empirical average annular viscosity based on several points across the annular gap.

Sifferman et al(7) reported that the cuttings experienced varying viscosity across the annular section due to changes in the velocity of the bulk fluid and of the cuttings relative to the fluid. The cuttings are "seeing" an effective viscosity that is due not only to the shear rate generated by the main bulk flow but also to its relative motion in the bulk flow.
d. Viscosity field due to a combination of particle settling and fluid motion

Above analysis has showed that both cuttings settling velocity and annular fluid velocity affect the fluid shear field around the settling particle. This will change the fluid effective viscosity for non-Newtonian fluids\(^{(9,10,11,26,78-80)}\). Therefore, both particle settling and fluid circulation will affect the particle settling velocity in actual practices.

In fact, it was proposed by Novonty\(^{(78)}\) through both experimental investigation and theoretical modelling of particle transport through dynamic non-Newtonian fluids that the vector sum of the shear rate by the cuttings settling and the shear rate caused by fluid motion should be used to calculate the effective shear rate for particle settling under dynamic flow conditions. Considering the shear rate by cuttings settling as \(\gamma_{sp} = v_s/d_s\), the effective shear rate imposed on the settling particle in dynamic non-Newtonian fluids is calculated by the following equation:

\[
\gamma_{eff} = \sqrt{\gamma_{sp}^2 + \gamma_{sf}^2}
\]

(7.1.10)

where \(\gamma_{sf}\) is the shear rate imposed by fluid motion. A similar treatment was reported by Hannah and Harrington\(^{(79)}\).

7.2 New experiments for particle settling velocity in dynamic drilling fluids

From the critical review of proppant transport in dynamic non-Newtonian fluids, it has been seen that although a reasonable theoretical treatment has been used by Novonty\(^{(78)}\), no reliable experimental data have been reported. In the view of the present author, Shah’s experimental method\(^{(76)}\) has been the best so far for dynamic particle settling velocity measurements though restrictions were imposed on the particles by a wire line to guide the movement of the particles. In this section, a new theoretical technique is proposed to derive cuttings settling velocity in dynamic non-Newtonian drilling fluids based on the experimental data for the MTV for vertical hole cleaning. These experimental data are then
used for the development of a new model for cuttings settling velocity in dynamic non-Newtonian drilling fluids.

7.2.1 Review of the concept of MTV for vertical hole cleaning

In chapter 3, the MTV required for efficient hole cleaning is defined as the velocity at or above which, all the cuttings can be transported up to the surface. For vertical wells, the necessary condition for this is that all the cuttings should be moving upward and no cuttings are sliding down along the borehole wall. It means that the fluid velocity across the annulus should be higher than or equal to the corresponding cuttings settling velocity i.e. all the cuttings have positive transport velocities towards the surface. Therefore, corresponding to the MTV, the fluid velocity at a special point of the annulus will be just equal to the cuttings settling velocity there due to the existence of fluid velocity profile as described in chapter 6. This point will be used to derive the cuttings settling velocity based on the experimental data of the MTV for vertical hole cleaning. Due to the fact that all the experimental data are conducted in actual flow conditions, the derived settling velocity is of course the cuttings settling velocity in dynamic non-Newtonian drilling fluids. The detailed derivation of the cuttings settling velocity data is discussed in the proceeding section.

7.2.2 Derivation of the cuttings settling velocity from the MTV for vertical hole cleaning

In this section, the detailed discussions are presented for the derivation of the cuttings settling velocity from the MTV for vertical hole cleaning.

a. Theoretical analysis

In chapter 6, the various flow equations for non-Newtonian Herschel-Bulkley fluids through concentric annuli are derived and presented. It was known that fluid flow across the annulus has the following characteristics:

- The fluid velocity is higher in the central region of the annulus than that in the region close to the borehole or pipe wall.
- The fluid effective viscosity is higher in the central region of the annulus than that in the region close to the pipe or borehole wall.

It is very clear that the cuttings in the wall regions experience a lower fluid viscosity. This may deduce that the cuttings settling velocity adjacent to the wall is higher than that in the central region of the annulus. It is also known that the fluid velocity close to the wall is much lower than that in the central part of the annulus. The combination of the above two phenomenon demonstrates that the transport velocity of the cuttings, which is expressed as the fluid point velocity minus the cuttings settling velocity as expressed in Eq. 2.1.1, will be much lower in the wall region than that in the central region.

\[ v_t = v_f - v_s \]  \hspace{2cm} (2.1.1)

Thus, corresponding to the MTV for vertical hole cleaning, the fluid velocity close to the wall should just be balanced by the particle settling velocity there. If the average fluid velocity is below the MTV for vertical hole cleaning, the cuttings in the wall region of the annulus will start sliding down first, which has been confirmed by the present experimental observations. Due to the fact that the fluid velocity profile is asymmetric to the hole axis, there are two possible positions at which the cuttings may start sliding down first. One is the cuttings close to the pipe wall and the other is the cuttings close to the borehole wall. In the present analysis, cuttings transport velocities in these two positions have been calculated respectively. It is found that the cuttings close to the borehole wall are the most difficult ones to be cleaned i.e., cuttings touching the borehole wall will be the most difficult cuttings to be transported up to surface. Therefore, in the following discussions, the cuttings settling velocity has been derived based on the fluid velocity close to the borehole wall. Corresponding to the criteria of the MTV, the fluid velocity approaching to the centre of the particle touching the borehole wall is equal to the particle settling velocity there. If this velocity is below the cuttings settling velocity in that region, some cuttings will start sliding downward. Otherwise, all the cuttings can be transported up to the surface and no cuttings will slide downward.
b. Assumptions

In the analysis of drilled cuttings transport, we are in fact dealing with a solid-liquid two phase flow. Enormous difficulties are involved for the analysis of a solid-liquid two phase flow, especially when the fluid is non-Newtonian. For example, how the existence of cuttings will affect the fluid viscosity and how the cuttings may affect the fluid velocity profile etc. To answer these questions, some special projects need to be set-up, which is beyond the scope of the present studies. Therefore, to derive the cuttings settling velocity, some assumptions are made to simplify the complicated process. The assumptions are:

- The annulus is concentric without drill pipe rotation.
- The cuttings in the annulus have no effect on the annular fluid flow profiles including the fluid velocity profile, shear rate profile and fluid viscosity profile.
- All cuttings are spherical particles and the cuttings concentration in the annulus is 2% by volume.

c. Derivation procedure of the cuttings settling velocity

Based on the above assumptions, the cuttings transport velocity can be calculated as the fluid velocity approaching the centre of the particle minus the particle settling velocity. Therefore, corresponding to the MTV for vertical hole cleaning, the fluid velocity approaching the centre of the particle touching the borehole wall will just balance the particle settling velocity there. Thus, the cuttings settling velocity corresponding to each of the experimental data conducted in vertical boreholes can be calculated using the following procedure:

- Compute the radius of the cuttings;
- Calculate the fluid velocity profile using the MTV and the corresponding experimental parameters;
- By assuming that the cuttings are touching the borehole wall, calculate the fluid velocity approaching to the centre of the cuttings. This velocity is the cuttings settling velocity in dynamic non-Newtonian drilling fluids;
• The fluid shear rate approaching to the centre of the cuttings touching the borehole wall is also calculated for the use of the model development.

For the calculations of the fluid velocity profile, the annular flow equations presented in chapter 6 are used for laminar flow regime. If the fluid is in turbulent flow regime, the fluid velocity profile is calculated based on the equations reported in Appendix A7.1 and A7.2, which are only for power law fluids.

Following the above procedure, the cuttings settling velocity for each set of experimental data for the MTV in vertical boreholes has been derived, which is used for the establishment of a new cuttings settling velocity model.

The present experimental measurements of cuttings settling velocity in dynamic flow conditions is in fact quite similar to that reported by Shah(76) for the measurements of proppant settling velocity under dynamic fracturing fluids. However, the improvements of the present study over Shah’s include:

• No artificial restrictions are imposed on the cuttings in order that the cuttings can be moving along a specified path.
• Shah(76) has used the central region of the pipe as the criteria for particle settling velocity measurements, where the shear rate imposed by fluid circulation in fact should be zero. Therefore what it was measured by Shah is particle settling in “static fluid” instead of dynamic fluids because of the zero shear rate imposed by fluid motion in the central region of the column. In the present study, the cuttings close to the wall have been examined, where fluid circulation has great effects on particle settling because of the higher shear rate imposed by fluid circulation.

During the present experiments, it is observed that the cuttings are either sliding downward or being smoothly transported up to the surface, especially when the pump rate is close to the flow rate corresponding to the MTV. The phenomenon for the cuttings movement in the annulus observed by Williams and Bruce(3), which can be seen from Fig. 7.2.1, were not observed by the present author. This has made the present experimental data more reliable
Fig. 7.2.1 The moving characteristics of various shaped cuttings in a vertical wellbore

a. Discs transported in turbulent flow (centre pipe stationary)
b. Small discs transported in viscous flow (centre pipe stationary)
c. Medium discs transported in viscous flow (centre pipe stationary)
d. Large discs transported in viscous flow (centre pipe stationary)
because the cuttings are being transported along a specified radial position, especially those close to the wall region of the annulus.

7.3 Development of a new mathematical model for cuttings settling velocity in dynamic drilling fluids

In the above section, cuttings settling velocities in dynamic drilling fluids have been derived based on the experimental data for the MTV in vertical holes. In this section the detailed development of a mathematical model for cuttings settling velocity in dynamic non-Newtonian drilling fluids are presented.

7.3.1 Assumptions

Due to the complexity of drilled cuttings transport process, the following assumptions have in fact been made during the derivation of the cuttings settling velocity data:

- The cuttings are well dispersed in the fluid so as not to interact with each other.
- The cuttings are spherical particles and don’t affect the fluid rheological properties.
- The presence of cuttings does not affect the fluid velocity profile in the annulus.
- The effective shear rate by fluid circulation for particle settling can be taken as the fluid shear rate approaching to the centre of the particle.
- The concentration of the drilled cuttings in the annulus is 2% by volume.

With these assumptions, the development of the mathematical model is greatly simplified. The two-phase annular flow can be treated as if there were no drilled cuttings there. The effects of cuttings and cuttings concentration on fluid rheological properties and fluid flow characteristics are neglected. Because of the low cuttings concentration in the annulus, the cuttings are not interacting with each other. Therefore, the cuttings can be treated as individual particles and no cuttings clusters are dealt with.

7.3.2 General model for particle settling velocity

First of all, the generalised particle settling velocity model is derived simply based on the forces balance. No assumptions are made for the fluid rheological models and fluid flow
regimes. Thus, the generalised settling velocity model can be used for any fluid at any flow regime.

**a. Forces acting on the cuttings**

Based on the above assumptions, two forces are acting on the cuttings in vertical wells as has been seen in section 3.2 of chapter 3:

The effective gravitational force \( F_g \), which can be expressed as:

\[
F_g = V_s \cdot (\rho_s - \rho_f) \cdot g
\]  

(3.2.1)

The fluid drag force \( F_D \), which may be expressed as:

\[
F_D = \frac{1}{2} C_D \rho_f v_s^2 A_p
\]  

(2.2.2)

It is these two forces which are affecting the settling velocity of drilled cuttings in non-Newtonian drilling fluids.

**b. Particle settling velocity model**

From the above two equations, it can be seen that the cuttings gravitational force is a constant while the fluid drag force is fluid drag coefficient \( C_D \) and cuttings settling velocity \( v_s \) dependant. The cuttings will settle downward under the action of the cuttings’ gravitational force \( F_g \) and the fluid drag force \( F_D \) is resisting the cuttings from settling. As the cuttings settling velocity increases, the fluid drag force \( F_D \) acting on the cuttings will be increased. This process continues until an equilibrium condition is reached, at which the fluid drag force will be equal to the cuttings gravitational force. From then on, the cuttings will settle at a constant velocity, which is called the cuttings settling velocity.

Equating the cutting’s gravitational force and the fluid drag force (Eqs. 3.2.1 and 2.2.2), the following equation can be obtained:

\[
V_s \cdot (\rho_s - \rho_f) \cdot g = C_D \cdot A_p \cdot \frac{\rho_f \cdot v_s^2}{2}
\]  

(7.3.1)

With the assumption that the cuttings are all spherical particles, the projected area \( A_p \) can be calculated by:
\[ A_p = \frac{\pi}{4} d_s^2 \]  
\[ (7.3.2) \]

and the volume of the particle can be calculated using:

\[ V_s = \frac{\pi}{6} d_s^3 \]  
\[ (7.3.3) \]

Replacing \( A_p \) and \( V_s \) into Eq. 7.3.1, the generalised model for cuttings settling velocity can be derived as:

\[ v_s = \left( \frac{4}{3} \frac{g}{C_D} \frac{(\rho_s - \rho_f) \cdot d_s}{\rho_f} \right)^{1/2} \]  
\[ (2.2.7) \]

Eq. 2.2.7 demonstrates that for a spherical particle, its settling velocity only depends on the fluid drag coefficient \( C_D \). For a special particle, its settling velocity can be easily calculated by Eq. 2.2.7 as long as the fluid drag coefficient \( C_D \) is known no matter what the fluid rheological properties are. This tells us that the modelling of cuttings settling velocity is in fact the modelling of the fluid drag coefficient \( C_D \).

### 7.3.3 Fluid drag coefficient \( C_D \)

Cuttings settling velocity model is in fact the correlation of the fluid drag coefficient \( C_D \) against the various drilling parameters. In section 2.2.1, it is known that for particle settling in Newtonian fluids, the fluid drag coefficient \( C_D \) for a spherical particle is only a function of particle Reynolds number \( N_{Rep} \). For the case of non-Newtonian fluids, it is speculated that the fluid drag coefficient \( C_D \) should also mainly be a function of the particle Reynolds number \( N_{Rep} \). From Eq. 2.2.7, the fluid drag coefficient \( C_D \) can be easily derived as:

\[ C_D = \frac{4.0 \cdot d_s \left( \frac{\rho_s}{\rho_f} - 1.0 \right) \cdot g}{3.0 \cdot v_s^2} \]  
\[ (7.3.4) \]

Thus, corresponding to each of the cuttings settling velocity data, the fluid drag coefficient \( C_D \) can be calculated by Eq. 7.3.4.
7.3.4 Particle Reynolds number $N_{Re_p}$

For a given cutting's settling velocity $v_s$, cuttings diameter $d_s$, effective viscosity of the fluid around the settling particle $\mu_e$, and the density of the fluid $\rho_f$, the particle Reynolds number $N_{Re_p}$ can be calculated by:

$$N_{Re_p} = \frac{d_s \cdot v_s \cdot \rho_f}{\mu_e} \quad (7.3.5)$$

For a Newtonian fluid, $\mu_e = \mu$, Eq. 7.3.5 will be the same as Eq. 2.2.4. However, for non-Newtonian fluids, the calculation of the effective viscosity around a settling particle is very complicated, which is discussed in the next section.

7.3.5 The effective viscosity around a settling particle

It has been known that the fluid drag coefficient $C_D$ can be easily calculated for a given particle settling velocity and particle size. However, for the calculation of particle Reynolds number, the fluid effective viscosity $\mu_e$ is still an unknown parameter. From the previous discussions, it has been shown that for non-Newtonian drilling fluids, the calculation of fluid effective viscosity has been a big problem. The flow field around a settling particle is not only affected by the settling velocity of the particle, but also affected by the fluid velocity profile. In order to derive a reliable model, both of these two effects must be considered. Therefore, in the present study, the effective viscosity has been calculated based on the vector sum of the shear rates acting on the fluid both by cuttings settling and by the fluid circulation.

(i) The shear rate imposed by a settling particle itself is calculated using the ratio of the settling velocity to the cuttings diameter as expressed in Eq. 7.1.4.

(ii) The shear rate imposed by the fluid motion can be calculated using the equation of fluid shear rate profile for non-Newtonian annular fluid flow. Due to the fact that the settling velocity is taken from the fluid point velocity through the centre of the particle touching the borehole wall, the shear rate there is also taken as the shear rate imposed by the fluid circulation, which has been expressed as $\gamma_{sf}$. 

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The effective shear rate imposed on the fluid around a settling particle is considered as the vector sum of these two shear rates as reported by Novonty(78):

\[ \gamma_{e_h} = \sqrt{\gamma_{sp}^2 + \gamma_{sf}^2} \]  

(7.1.10)

Thereafter the effective viscosity of the fluid around the settling particle is calculated using Eq. 7.3.6 for power law fluids:

\[ \mu_e = K \cdot (\gamma_{eh})^{n-1.0} \]  

(7.3.6)

Then, the particle Reynolds number for each set of cuttings settling velocity data is calculated by Eq. 7.3.5.

7.3.6 New model for particle settling velocity in dynamic fluids

It has been realised that the establishment of the cuttings settling velocity model is in fact the correlation between the fluid drag coefficient \( C_D \) and particle Reynolds number \( N_{Rep} \).

Based on the above discussions, the experimental data have been processed so that a series of \( C_D \) and \( N_{Rep} \) have been produced. The experimental data used in the present correlations are confined into the following categories:

- Concentric annuli of various sizes without pipe rotation;
- Both laminar and turbulent flow regimes;
- 2% cuttings concentration by volume.

The results have been plotted in Fig. 7.3.1, which demonstrates that a very good correlation exists between \( C_D \) and \( N_{Rep} \). For a log-log co-ordinate system, when the particle Reynolds number is below 11.2, the relationship between \( C_D \) and \( N_{Rep} \) is linear. As the particle Reynolds number is above 11.2, \( C_D \) becomes a constant. This trend is exactly the same as that for particle settling in Newtonian fluid as shown in Fig. 2.2.1. It is obvious that as has been discussed by Luo(26), for a general case, the fluid drag coefficient \( C_D \) may be correlated against the particle Reynolds number \( N_{Rep} \) as:
Fig. 7.3.1 Fluid drag coefficient CD versus particle Reynolds number for cuttings settling in dynamic non-Newtonian fluids.

- Laminar flow
- Turbulent flow

Conditions:
- Concentric annuli
- 2% cuttings concentration
- 0 pipe rotary speed
Using regression analysis, the following relationships between $C_D$ and $N_{Rep}$ may be obtained at different cuttings settling regimes.

**In laminar settling regime:**

$$C_D = \frac{5.782}{N_{Rep}^{0.9894}} \quad (N_{Rep} < 11.22)$$  \hspace{1cm} (7.3.8)

**In turbulent settling regime:**

$$C_D = 0.527 \quad (N_{Rep} \geq 11.22)$$  \hspace{1cm} (7.3.9)

Eqs. 7.3.8 and 7.3.9 are the correlations between fluid drag coefficient $C_D$ and the particle Reynolds number $N_{Rep}$ for cuttings settling in dynamic non-Newtonian drilling fluids. They are, in fact, the newly proposed model for cuttings settling in dynamic non-Newtonian drilling fluids.

It needs to be pointed out that the critical particle Reynolds number, which is 11.22 in the present model, is obtained by the interception of Eq. 7.3.8 and Eq. 7.3.9. This means that the cuttings are either settling in laminar regime or settling in turbulent regime. The transition regime has been discarded. It also needs to be realised that the so-called laminar or turbulent regime for cuttings settling is referred to the particle settling regime. It may not necessarily coincide with the fluid flow regime.

### 7.4 Verifications of the new cuttings settling velocity model

In section 7.2.2, it has been seen that the present experimental data for cuttings settling velocity were not directly measured during the experiments but derived from the MTV for vertical hole cleaning. In order to verify the present study, the comparison is also made between the directly measured data and the model predictions i.e. between the measured MTV for vertical hole cleaning and the predicted MTV using the newly developed cuttings settling velocity model. As a further verification of the newly proposed model, the present model is also compared against the previous correlations.
7.4.1 Prediction procedure of the MTV for vertical hole cleaning

Before making the comparison between the predicted MTV and the measured MTV for vertical hole cleaning, first of all, the MTV for vertical hole cleaning should be predicted corresponding to each of the experimental data collected for the dynamic settling velocity measurements. As has been discussed in section 7.2.2 for the derivation of the cuttings settling velocity data, at the MTV, the fluid point velocity approaching the centre of the cuttings touching the borehole wall should just balance the cuttings settling velocity there. The detailed procedure for the MTV predictions is now discussed as follows:

(i) Assume MTV=\(v_f\);

(ii) Calculate the fluid velocity \(v_p\) and fluid shear rate \(\gamma_{sf}\) approaching the centre of the particle touching the borehole wall using the various annular flow profiles for Herschel-Bulkley fluids presented in chapter 6 for laminar flow regime and using the equations presented in Appendix A7.1 and A7.2 for turbulent flow regime;

(iii) Calculate the particle settling velocity \(v_s\). First of all, assume the particle settling velocity as \(v_s\). Calculate the shear rate by particle settling by Eq. 7.1.4. Then, compute the effective shear rate and effective viscosity for particle settling by Eq. 7.1.10 and Eq. 7.3.6 respectively. Calculate the particle Reynolds number by Eq. 7.3.5. Compute the fluid drag coefficient by Eq. 7.3.8 or 7.3.9 based on the particle Reynolds number concerned. Thereafter, compute the new settling velocity \(v'_s\) by Eq. 2.2.7. If \((v_s=v'_s)\), then \(v_s\) is the cuttings settling velocity. Otherwise, let \(v_s=v'_s\) and repeat step (iii) again until \(v_s\) converges.

(iv) If \((v_s=v_p)\), then \(v_f\) is the MTV. Otherwise, using fluid point velocity through the centre of the particle touching the borehole wall \(v_p=v_s\) to calculate the average fluid velocity \(v'_f\). Thereafter, let \(v_f=v'_f\) and repeat step (i) again until it converges.

7.4.2 Comparison of the predicted MTV and the measured MTV

Following the above procedure, the MTV required for vertical hole cleaning has been predicted corresponding to each of the experimental data collected during the cuttings transport experiments. The measured MTV against the predicted MTV have been plotted in
Fig. 7.4.1, which shows that the experimental data are in a good agreement with the model predictions. The average relative error percentage, which is calculated using Eq. 7.4.1, is only 18.6% for all the experimental data concerned. This has verified the present settling velocity model and it has also demonstrated that the newly proposed settling velocity model can be used to predict cuttings settling velocity in dynamic non-Newtonian drilling fluids with confidence.

$$\text{Err}\% = \frac{\text{predicted} - \text{measured}}{\text{predicted}} \times 100.0$$  \hspace{1cm} (7.4.1)

### 7.4.3 Comparison of the present model against the previous models

Section 7.4.2 has showed that the present model has well represented the present experimental data. Then followed, comparison is made between the present model and the previous settling velocity models, which include:

- Stokes' Law and Newton's law for particle settling in Newtonian fluids;
- Peden and Luo's model\(^{(18)}\) for particle settling in power law fluids.

For the different settling velocity models, the correlations between \(C_D\) and \(N_{Rep}\) have been plotted in Fig. 7.4.2, which shows that significant differences exist among the three different model correlations.

In laminar flow regime, the present correlation is deviated from the Stokes' law but it is literally parallel to the Stokes' law. This demonstrates that the present model has nearly the same slope as Stokes' law but has quite different intercepts. In turbulent flow regime, the present correlation is quite the same as Newton's law, which can be clearly seen from Fig. 7.4.2.

Peden and Luo's model has also been compared with Stokes' Law. It can be seen that these two models are intercepting each other i.e. these two models have quite different slopes in laminar flow regime. As a matter of fact, except for the particle Reynolds number of 0.01 to 1.0, Peden and Luo's correlation has greatly deviated from the Stokes' law.

The above analysis shows that the present correlation is more representative to the Stokes' law than Peden and Luo's model. However, a simple question one may ask is that why the
**Fig. 7.4.1** Measured MTV against the predicted MTV for vertical hole cleaning using the new cuttings settling velocity model

- New model: Laminar flow
- New model: turbulent flow
- Stokes' law
- Newton's Law
- Peden & Luo's Correlation

**Fig. 7.4.2** Comparison of the different correlations of fluid drag coefficient and particle Reynolds number for particle settling
new model has a different intercept as Stokes' law does. Because Stokes' law was theoretically derived and has been well accepted for particle settling in Newtonian fluids, $C_D$ versus $N_{Re}$ supposes to follow Stokes' law in laminar flow regime no matter what the fluid rheological properties are. The reasons for the deviation of the present $C_D$ versus $N_{Re}$ correlation from the Stokes' law may include the following aspects:

a. **Different types of fluids**

Stokes' law was derived for particle settling in Newtonian fluids which have a constant viscosity no matter what the shear rate acting on the fluids is. However, the present model is established for particle settling in non-Newtonian drilling fluids, which are shear thinning in rheology. Though the effective viscosity has been used for the calculations of particle Reynolds numbers, the equations used may not reflect the true effective fluid viscosity around the cuttings. In fact, the fluid viscosity around a settling particle should be much more complicated than the representations of Eqs. 7.1.10 and 7.3.6. This may contribute to the deviation of the present model from the Stokes' law.

b. **Wall effect**

Stokes' law is for the settling of a single particle in an infinite medium. However, the present experimental data were collected for particle settling in concentric annuli. As has been reported by previous researchers$^{(18)}$, the existence of a wall will affect the settling velocity of the particle.

c. **Effect of cuttings concentration**

Stokes' law is for a single particle settling. However, the present experiments have been conducted using 2% cuttings concentration. Surely, the existence of large amount of cuttings will not only affect the fluid viscosity and it will also increase the possibility of interactions of the cuttings. These two effects will of course affect the cuttings settling velocity obtained. Accordingly, this will affect the settling velocity model developed.
d. Effect of cuttings shape

Stokes' law is for spherical particles. The present study has used gravel sand as the simulated cuttings. Though in the model development it has been assumed that the gravel sands are spherical in shape, in actual practices, the gravel sand is varied in shape from one particle to another.

7.5 Extension of the MTV predictions using the newly proposed model

Section 7.4.1 presented the detailed procedure for the predictions of MTV for vertical hole cleaning using the newly proposed cuttings settling velocity model. But, it was limited into the following conditions:

a. Concentric annuli without drill pipe rotation;
b. 2% cuttings concentration by volume.

However, in actual drilling practices, the drill pipe may be rotated and it may also offset toward the borehole wall to become eccentric annuli. The rate of penetration may be varied in a wide range as well. In order to expand the applicability of the present study, these effects need to be analysed so that the MTV for vertical hole cleaning can be predicted at more realistic conditions.

7.5.1 Effect of pipe eccentricity and pipe rotary speed

Though in the model development, only the cuttings settling velocity data in concentric annuli without pipe rotation have been used, it can be extended into the MTV predictions in eccentric annuli as long as the fluid velocity and shear rate profile can be calculated. However, due to the different velocity profile in eccentric annuli, the calculation criteria for the MTV will be different from that for concentric annuli. Because of the minimum fluid velocity in the smallest annular clearance, the prediction of the MTV in eccentric annuli will be based on the particle touching the borehole wall in the smallest annular clearance.

In the present analysis, the annular flow modelling of Herschel-Bulkley non-Newtonian fluids through concentric annuli with pipe rotation and through eccentric annuli
with/without pipe rotation developed by Laruccia\(^{(87)}\) has been used. The source codes were initially written in Pascal. They were translated into FORTRAN by the present author in order to incorporate them into the final computer package for hole cleaning design and analysis, which is discussed in chapter 10.

From the prediction procedure of MTV for vertical hole cleaning, it has been seen that one important step is to calculate the average fluid velocity based on the point velocity approaching the centre of the cuttings touching the borehole wall. This has been easily tackled for concentric annular flow without pipe rotation. However, for concentric annuli with pipe rotation or eccentric annuli with/without pipe rotation, it has become the major obstacle for the extension of the MTV predictions.

After an extensive analysis, the present author has found that a simple linear relationship exists between the average fluid velocity and the point velocity and point shear rate in a special point of the annulus for a given hole geometry and other drilling parameters. This holds true for both concentric annuli with pipe rotation and eccentric annuli with/without pipe rotation as shown in Fig. 7.5.1 for the fluid point velocity and Fig. 7.5.2 for the fluid shear rate. With the special correlations, the predictions of MTV for eccentric annuli have become possible. It has also made the extension become practical due to the much reduced CPU time. Previously, a lot of iterations are required for the calculation of the MTV. For each iteration, the fluid velocity profile and fluid shear rate profile need to be calculated, which takes a lot of computer time. However, with the present correlations, at the beginning of the MTV predictions, two fluid velocity profiles and shear rate profiles need to be computed at two different average fluid velocities. Then, the correlation between the point velocity approaching the centre of the cuttings touching the borehole wall and the average fluid velocity and the correlation between the point shear rate approaching the centre of the cuttings touching the borehole wall and the average fluid velocity will be obtained as has been shown in Figs. 7.5.1 and 7.5.2. Thereafter, during each iteration, the new point velocity will be directly used to calculate the average fluid velocity based on the correlation obtained. Thereafter, the shear rate can be easily derived using the average fluid velocity. So, much time can be saved.
Fig. 7.5.1 Relationship between fluid point velocity and average fluid velocity in eccentric annulus with pipe rotation

Fig. 7.5.2 Relationship between fluid point shear rate and average fluid velocity in eccentric annulus with pipe rotation
7.5.2 Effect of cuttings concentration

It has been known that the settling velocity model is developed using 2% cuttings concentration data. However, in the present study, the cuttings concentration has been varied from 1% to 4% by volume. Based on the experimental data, a correction correlation has been derived so that the MTV can be modified for the corresponding rate of penetration. The effect of rate of penetration of the MTV for vertical hole cleaning has in fact been considered together with the MTV for cuttings suspension in deviated wells, which is discussed in section 8.2.7.

7.6 Application of the new settling velocity model

A new model for cuttings settling velocity in dynamic non-Newtonian drilling fluids has been derived and discussed. The major applications of the present studies is now highlighted.

7.6.1 Cuttings settling velocity profile and transport velocity profile across the annulus

As has been known, the newly developed cuttings settling velocity model is a model for cuttings settling in dynamic non-Newtonian drilling fluids. In the calculation of the fluid effective viscosity around a settling cutting, the model has taken both the shear field by fluid motion and the shear field by the settling cutting itself into consideration. In chapter 6, it is known that both the fluid velocity and shear rate across the annulus are radial position dependent, which may deduce that a cuttings settling velocity profile may exist across the entire annular space. That is, the cuttings settling velocity should vary from position to position in the annulus if the circulating fluid is non-Newtonian. This, combined with the fluid velocity profile in the annulus, will produce a cuttings transport velocity profile, which can be calculated by the fluid point velocity $v_p$ minus the cuttings settling velocity at the specified radial position in the annulus:

$$v_t = v_p - v_s \quad (7.6.1)$$

The importance of calculating the cuttings settling velocity profile and cuttings transport velocity profile is obvious. They can provide a clear picture of the cuttings movement
across the entire annular space. Therefore, the time required for removing all the cuttings out of the borehole can be predicted quite accurately. This is probably no more so than making connections. The well will be circulated for a few minutes before a connection to clear cuttings away from the bottom hole assembly. Additionally "bottom up" annulus hole volume is circulated before tripping the bit out of the hole. Hole cleanliness and "fill" will be checked by a "wiper trip" before running casing.

In the following analysis, some examples are used to illustrate the cuttings settling and transport velocity profiles at various simulated conditions. Figs. 7.6.1 and 7.6.2 respectively show the cuttings settling velocity profile and cuttings transport velocity profile through a concentric annulus for power law fluid. It is very clear that as the cuttings approach the central region of the annulus, the settling velocity significantly decreases due to the low shear rate caused by fluid motion. Obviously, the cuttings transport velocity in the central region of the annulus is much higher than that in the wall regions of the annulus. In this special case, in about 60% of the annulus, the cuttings are transporting at a velocity higher than the average fluid velocity, which demonstrates that the average fluid velocity and cuttings settling velocity can not be used to effectively evaluate vertical hole cleaning efficiency.

Figs. 7.6.3 and 7.6.4 show the cuttings settling and transport velocity profile in a concentric annulus for Bingham plastic fluid. It can be seen that there is a unsheared plug in the central region of the annulus, at which both the cuttings settling velocity and the cuttings transport velocity are the same across the unsheared plug. Finally, for an eccentric annulus without pipe rotation, an example has been shown in Figs. 7.6.5 and 7.6.6. As expected, in the smaller annular area, the cuttings have a very low transport velocity. In actual practices, attention must be paid into those cuttings which are in the narrow region of the eccentric annulus. In order to have a perfect hole cleaning, those cuttings must be transported into the surface.
7.6.2 Predictions of the MTV for vertical hole cleaning

Section 7.4.1 has presented the detailed procedure for the predictions of MTV for concentric annuli without pipe rotation and at a cuttings concentration of 2% by volume using the newly proposed cuttings settling velocity model. Then, in section 7.5, the predictions of MTV have been extended into eccentric annuli with/without pipe rotation and concentric annuli with pipe rotation. It has also been extended into a wide range of rate of penetration. The MTV is in fact the minimum transport velocity required for effective hole cleaning in vertical wells, for at which all the cuttings can be transported up to the surface and no cuttings will slide downward along the borehole wall. The analysis of the MTV at different operating conditions is discussed in the following section.

7.6.3 Sensitivity analysis of the various drilling parameters on the MTV

As discussed in chapter 5, for the evaluation of hole cleaning efficiency, it is assumed that the lower the MTV, the higher the hole cleaning efficiency. In actual drilling operations, the drilling parameters can be adjusted so as to produce a lower MTV for an improved hole cleaning. Some examples are used to demonstrate how the various drilling parameters will affect the MTV i.e. vertical hole cleaning, which can be seen from Figs. 7.6.7 through 7.6.10.

Fig. 7.6.7 shows the effect of fluid consistency index \( K \) on the MTV for vertical hole cleaning. It can be seen that for a given operational condition, as the fluid consistency index \( K \) increases, the MTV will be increased until a maximum MTV is reached. Thereafter, the MTV will be decreased with a further increase in the \( K \) value. This shows that either low viscosity or high viscosity fluid can provide a better hole cleaning. A worst transport fluid exists which may provide the highest MTV i.e. poorest cuttings transport. This range of fluid viscosity should be avoided in actual drilling operations.

The effect of fluid non-Newtonian index \( n \) on the MTV is plotted in Fig. 7.6.8, which shows that as the \( n \) value increases, the MTV will be greatly decreased i.e. hole cleaning
will be greatly improved. This reveals that the shear thinning property of the drilling fluids is not favourable to efficient cuttings transport.

Fig. 7.6.9 has showed the effect of cuttings size on the MTV, which demonstrates that as the particle size increases, the MTV will be increased. The effect of borehole diameter on the MTV is shown in Fig. 7.6.10, which shows that the MTV increases with an increase in wellbore diameter. Therefore, it may be concluded that the hole can be most efficiently cleaned by using a smaller drill bit or larger drill pipe.

7.6.4 Radial cross-section analysis of the MTV

Based on the definition of the MTV for vertical hole cleaning, it can be seen that the criteria for the MTV predictions are:

- It is based on the cuttings touching the borehole wall. This is the worst transport point in the annulus. The cuttings there are the most difficult cuttings to be transported up to the surface.
- Total hole cleaning can be achieved if the pump rate can exceed the predicted MTV.

In actual practices, the MTV required for vertical hole cleaning may not be achieved due to the limitations of drilling facilities or the restrictions of other factors. For example, the pump can not achieve such a high pump rate. As has been discussed, the MTV is the minimum fluid velocity required to clean all the drilled cuttings out of the borehole. If the MTV can not be reached, some cuttings will slide down along the borehole and can not be transported up to the surface. Therefore, an obvious question one may ask is what the hole cleaning situation will be if the MTV can not be achieved.

In this section, an analysis is carried out for the effect of cuttings radial positions on the MTV. Rather than calculating the MTV at the radial position of the cuttings touching the borehole wall, the MTV is to be calculated based on the different cuttings radial positions across the annulus. This will clearly show us the sensitivity of the MTV on the calculation criteria. It also shows us that even when the actual pump rate can not reach the MTV, only
a very small proportion of the annulus can not be cleaned and over 90% of the annulus may still be perfectly cleaned.

Fig. 7.6.11 shows the effect of cuttings radial positions on the MTV for vertical hole cleaning. It shows that as the cuttings are moving towards the central region of the annulus, the MTV is significantly reduced because of the combination of high fluid velocity and high fluid viscosity.

7.7 Discussions

How to effectively clean the drilled cuttings out of the borehole is the main reason for the study of drilled cuttings transport. In the literature review, it has been seen that contrary conclusions for efficient cuttings transport in vertical wells have been concluded by the previous researchers, which can be seen from Table 2.9.1 for the effect of fluid viscosity and fluid flow regime. In this section, the reasons why different researchers have made the different conclusions are discussed. The effect of unsheared plug on vertical hole cleaning efficiency is analysed.

7.7.1 The preferred fluid viscosity and fluid flow regime

Whether high viscosity fluid in laminar flow or low viscosity fluid in turbulent flow will provide a better vertical hole cleaning is still at debate. Some researchers\(^{(2,3,6)}\) suggested that low viscosity fluid in turbulent flow will provide a better transport than that high viscosity fluid in laminar flow regime. However, most of the other researchers concluded that higher viscous fluid always gives a better hole cleaning, which is reasoned that high viscous fluid will induce a lower cuttings settling velocity.

Prokop\(^{(2)}\) reasoned without any experimental evidence that the flatter velocity profile in turbulent flow regime resulted in more cuttings being removed at higher transport velocities. Thus, it was concluded that turbulent flow would give a better cuttings transport.

Williams and Bruce\(^{(3)}\) and Zeidler\(^{(6)}\) experimentally investigated cuttings transport in vertical wells. By injecting some cuttings into the bottom of the annulus, the fluid was
**Fig. 7.6.5** Cuttings settling velocity profile in an eccentric annulus for power law fluids

**Fig. 7.6.6** Cuttings transport velocity profile in an eccentric annulus for power law fluids

**Fig. 7.6.7** Effect of fluid consistency index $K$ on the MTV for vertical hole cleaning

**Fig. 7.6.8** Effect of fluid non-Newtonian index $n$ on the MTV for vertical hole cleaning
Fig. 7.6.9 Effect of cuttings diameter on the MTV for vertical hole cleaning

Fig. 7.6.10 Effect of borehole diameter on the MTV for vertical hole cleaning

Fig. 7.6.11 Effect of cuttings radial position on the MTV for vertical hole cleaning
circulated at a constant velocity. Then, the cumulative cuttings recovered and the corresponding time were plotted. The slope of the curve was used as the measure of hole cleaning efficiency. It was regarded that the steeper the slope, the better the cuttings transport. This concept in fact indicated that as long as the cuttings are transported at roughly the same velocity, a better hole cleaning can be obtained. This obviously will be misleading. Even without experimental data, it can be easily deduced that in turbulent flow regime, because of the flatter velocity and viscosity profile, the cuttings transport velocity will not be much different. Therefore, as long as the fluid velocity is high enough to transport the cuttings, a steeper slope of the curve of cumulative cuttings recovered against time will be obtained i.e. a better hole cleaning can be obtained. This is obviously not true.

Based on the present study, whether laminar flow regime or turbulent flow will provide a better hole cleaning depends on the level of the fluid viscosity and other drilling parameters. It is found that there is a worst fluid viscosity region at which the MTV required is the highest. The experimental data showed that low viscosity in turbulent flow regime can provide a better hole cleaning than the worst viscosity region. However, high viscosity in laminar flow regime can always outperform low viscosity fluid in turbulent flow regime in hole cleaning for concentric annuli.

However, in normal drilling operations where the density requirement is greater than water, a minimum suspension properties are required to support the weighting agents. This precludes the low viscosity fluids i.e. required for turbulent flow regime.

7.7.2 The un-sheared plug versus cuttings transport

During vertical hole drilling operations, field experience has indicated that the wider unsheared plug in the annulus caused by high yield point is favourable to hole cleaning. This can now be fully explained theoretically. The present modelling results have showed that the cuttings settling velocity inside the drilling annulus is varied widely. Cuttings close to the centre region of the annulus, because of the low shear rate imposed by fluid motion, have a lower settling velocity. The cuttings close to the annular walls have a higher settling velocity. Therefore, the cuttings in the wider unsheared plug, because of the zero shear rate
imposed by fluid motion, will have a lower settling velocity i.e. more cuttings can be transported at a higher fluid velocity. Therefore a better cuttings transport can be obtained, which can be seen from Fig. 7.6.3 for the cuttings settling velocity profile and Fig. 7.6.4 for the cuttings transport velocity profile.
CHAPTER 8
DEVELOPMENT OF THE MTV MODELS DESCRIBING DRILLED CUTTINGS TRANSPORT IN DEVIATED WELLS

In the preceding chapter, a new model for cuttings settling velocity in dynamic non-Newtonian drilling fluids is developed. This model has also been used to predict the MTV required for efficient vertical hole cleaning. In deviated wellbores, two kinds of mechanisms for the removal of the drilled cuttings have been identified and experimentally investigated in chapter 5. In this chapter, two mathematical models are developed to describe the MTV required for deviated hole cleaning. One is the MTV model for cuttings suspension and the other is the MTV model for cuttings rolling. These two models are developed based on the physical balance of forces acting on the cuttings resting on the low-side annular wall. Two classic concepts - fluid drag force and fluid lift force are directly used to define the two criteria for the initiations of cuttings movement inside an inclined drilling annulus.

8.1 Overview of the theoretical modelling by previous researchers

In section 2.5.2, the various theoretical models developed by the previous researchers\cite{24,25,72,85} describing deviated hole cleaning have been analysed and critically discussed. It was concluded that limitations exist for each of the theoretical models developed. In the view of the present author, these models can not describe the cuttings transport process accurately, especially when being extended into a wide range of operating conditions. Therefore, more theoretical studies are required for a better understanding of the cuttings transport process.
8.2 Development of the mathematical MTV models

During deviated hole drilling operations, the cuttings transport process is considerably more complicated than that in vertical wells as described in chapter 7. Mathematical models are useful tools to predict cuttings transport process and to anticipate the potential drilling problems if there are any. In this section, the development of the two mathematical models describing drilled cuttings transport in deviated wellbores are presented, details of which can also be seen from two publications(74, 84).

8.2.1 Brief review of the force balance MTV models

In chapter 3, new concepts have been defined for adequate hole cleaning in deviated wells - the MTV, which is defined as the minimum transport velocity at or above which, all the cuttings are moving forward in a deviated wellbore and no stationary cuttings or sliding down cuttings exist in the annulus. Two criteria have been identified which satisfy the above conditions. One is the MTV for cuttings suspension and the other is the MTV for cuttings rolling. In this section the basic force balance models describing both the MTV for cuttings suspension and the MTV for cuttings rolling presented in section 3.3.3 are briefly reviewed.

a. The force balance MTV model for cuttings suspension

The formation of a cuttings bed on the low-side annular wall has been the major concern for deviated hole cleaning. The analysis in section 3.3.1 has showed that as long as the cuttings can be suspended within the drilling fluid, they can be transported up to the surface. In order to remove the drilled cuttings out of a deviated borehole, the most obvious transport mechanism will be that all the cuttings can be suspended within the drilling fluid. In section 3.3.3, it has been shown that the fluid velocity to achieve the MTV for cuttings suspension is expressed as:

\[
C_L \cdot A_L \cdot \frac{\rho_f \cdot v_p^2}{2} = V_s \cdot (\rho_s - \rho_f) \cdot g \cdot \sin(\Phi)
\]

(3.3.15)

where \( C_L \) is the fluid lift coefficient; \( v_p \) the fluid point velocity approaching the centre of the particle resting on the low-side annular wall; \( \Phi \) the hole angle. Eq. 3.3.15 is now called the
force balance MTV model for cuttings suspension. As a matter of fact, the left side of Eq. 3.3.15 is the fluid lift force and the right side of the above equation is the component of the effective gravitational force acting vertically to the hole axis. In the following analysis, Eq. 3.3.15 is analysed and the MTV model for cuttings suspension is established using the correlation of fluid lift coefficient \( C_L \) and particle Reynolds number \( N_{Rep} \).

**b. The force balance MTV model for cuttings rolling**

It is true that if the cuttings can be suspended within the drilling fluid, a good hole cleaning can be obtained in deviated wells. However, in actual practices, the MTV required to suspend the cuttings in the fluid may not be achieved i.e. a cuttings bed may be formed on the low-side annular wall. If the fluid velocity is high enough, the cuttings bed will still be moving upward and no stationary cuttings exist in the annulus. The MTV for the initiation of cuttings moving bed or rolling has also been physically defined in section 3.3.3, which is expressed as:

\[
C_D \cdot A_p \cdot \frac{\rho_p v_p^2}{2} = F_g \cos(\Phi) + (F_g \sin(\Phi) - C_L A_L \frac{\rho_p v_p^2}{2}) \cdot f_i \quad (3.3.17)
\]

Eq. 3.3.17 is the force balance model for cuttings rolling forward. It shows that except for the fluid drag force, which is the left side of the equation, fluid lift force and the friction force between the cuttings and the low-side annular wall are also affecting the MTV for cuttings rolling. The fluid velocity which satisfies Eq. 3.3.17 is the MTV for cuttings rolling.

It needs to be pointed out that both Eq. 3.3.15 and Eq. 3.3.17 are directly derived from the balance of forces acting on the cuttings and no assumptions were made on the fluid rheology and fluid flow regime. Therefore, the two force balance models can be used for any fluid at any fluid flow regime.

**8.2.2 Assumptions**

From Eqs. 3.3.15 and 3.3.17, it can be seen that the MTV models are complicated and they can not be simply solved theoretically without any assumptions. Therefore, some similar
assumptions as that in section 7.3.1 for the development of cuttings settling velocity model are made:

- The drill pipe is concentric and not rotating.
- The cuttings are well dispersed in the fluid so as not to interact with each other.
- The cuttings don’t affect the fluid rheological properties.
- The cuttings are spherical in shape.
- The presence of cuttings does not affect the fluid velocity and viscosity profile in the annulus.
- The effective viscosity and fluid velocity to produce the fluid drag force and lift force can be calculated by the fluid velocity and viscosity acting through the centre of the cuttings.

From the above assumptions, it is understood that the cuttings will not affect the fluid flow characteristics and have no effect on the fluid properties. With these assumptions, we in fact can treat two phase flow problem as a pure fluid flow, which will greatly simplify the present problem.

For a spherical cutting, the effective area for both fluid drag force and fluid lift force can be expressed as:

\[ A_L = A_p = \frac{\pi}{4} d_s^2 \]  

(8.2.1)

Its volume \( V_s \) is expressed as:

\[ V_s = \frac{\pi}{6} d_s^3 \]  

(7.3.3)

8.2.3 Fluid lift coefficient \( C_L \) and particle Reynolds number for cuttings suspension

As has already been described that fluid lift force has directly been used for the development of the MTV model for cuttings suspension, the fluid lift coefficient \( C_L \) and particle Reynolds number \( N_{Rep} \) are now derived and discussed.
a. The fluid lift coefficient $C_L$

Replacing Eqs. 8.2.1 and 7.3.3 into Eq. 3.3.15, it can be derived that:

$$C_L = \frac{3 \cdot d_s \cdot \left( \frac{\rho_s}{\rho_f} - 1.0 \right) \cdot g \cdot \sin(\Phi)}{4 \cdot v_p^2}$$  

Eq. 8.2.2 is the equation for the calculations of the fluid lift coefficient $C_L$. It shows that for a given experimental data, the fluid lift coefficient $C_L$ can be calculated. However, it needs to be pointed out that $v_p$ in the above equation is the fluid velocity approaching to the centre of cuttings resting on the low-side annular wall. In fact, this velocity should be the relative velocity between the cuttings and the fluid there. Due to the complexity and uncertainty concerning the transport velocity of the cuttings close to the low-side annular wall, the fluid velocity $v_p$ approaching the centre of the cuttings resting on the low-side annular wall has been used for the calculation of the fluid lift coefficient in the present studies.

b. Particle Reynolds number $N_{Re_p}$

Particle Reynolds number for cuttings suspension is defined as:

$$N_{Re_p} = \frac{v_p \cdot \rho_f \cdot d_s}{\mu_e}$$  

where $\mu_e$ is the fluid viscosity approaching the centre of the cuttings resting on the low-side annular wall. It can be seen that for a given experimental data, a corresponding particle Reynolds number $N_{Re_p}$ can be calculated as well.

It has been demonstrated that for a given set of experimental data of MTV for cuttings suspension, a corresponding set of fluid lift coefficient $C_L$ and particle Reynolds number $N_{Re_p}$ can be obtained. The correlation between the fluid lift coefficient $C_L$ and particle Reynolds number $N_{Re_p}$ for cuttings suspension is discussed in section 8.2.5.
8.2.4 Fluid drag coefficient $C_D$ and particle Reynolds number $N_{Rep}$ for cuttings rolling

a. Fluid drag coefficient $C_D$

Similar to the derivation of the expression for the fluid lift coefficient $C_L$, the fluid drag coefficient $C_D$ can be obtained from the force balance equation for cuttings rolling Eq. 3.3.17. It is expressed as:

$$C_D = \frac{4}{3} \frac{d_s \left( \frac{\rho_s}{\rho_f} - 1 \right) \cos(\Phi) + f_s \sin(\Phi)}{v_p^2} - C_L \cdot f_i \quad (8.2.4)$$

where the fluid point velocity $v_p$ is the relative velocity between the cuttings and the fluid approaching to the centre of the particles resting on the low-side annular wall. Because of the fact that for the initiation of cuttings rolling, the cuttings are just started moving so that the cuttings transport velocity can be assumed as zero. Therefore, $v_p$ can be simply taken as the fluid point velocity there. Although the same $v_p$ has been used for cuttings suspension and cuttings rolling, the use of the fluid velocity $v_p$ approaching the centre of the cuttings resting on the low-side annular wall for cuttings rolling/sliding is more sound than that for cuttings suspension.

b. Particle Reynolds number $N_{Rep}$

The expression of the particle Reynolds number $N_{Rep}$ for cuttings rolling is the same as that for cuttings suspension, which has been shown in Eq. 8.2.3. As in the case of particle Reynolds number for cuttings settling velocity, the fluid viscosity around the cuttings on the low-side annular wall is affected by both the fluid velocity field and the existence of the particle itself. The shear rate by fluid flow is represented by $\gamma_{sf}$, which can be calculated using the annular flow equations. The shear rate by the existence of the particle can be calculated by the ratio of the relative velocity between the particle and the fluid to the particle diameter $d_s$. In the present case, the relative velocity between the particle and the fluid can be simply taken as the fluid point velocity $v_p$. Therefore, $\gamma_{sp}$ can be calculated by:
\[ \gamma_{sp} = \frac{v_p}{d_s} \]  

(8.2.5)

The effective shear rate acting on the fluid around the cuttings can then be calculated by:

\[ \gamma_{efh} = \sqrt{\gamma_{sp}^2 + \gamma_{sf}^2} \]  

(7.1.10)

For power law fluid, the effective viscosity can be calculated by:

\[ \mu_e = K \cdot (\gamma_{efh})^{n-1.0} \]  

(7.3.6)

Thereafter, the particle Reynolds number for cuttings rolling can be calculated using Eq. 8.2.3.

### 8.2.5 Correlations of \( C_L/N_{Rep} \) and \( C_D/N_{Rep} \)

The fluid drag coefficient \( C_D \) and fluid lift coefficient \( C_L \) and their corresponding particle Reynolds numbers have been introduced in the above discussion. Then followed, the calculation procedures for \( C_D/N_{Rep} \) and \( C_L/N_{Rep} \) and their correlations using the present experimental data are discussed. At the first stage of the correlation development, the experimental data are confined in the categories of:

- Concentric annuli of various sizes without drill pipe rotation;
- Constant cuttings concentration of 2% by volume;
- Both laminar and turbulent fluid flow regime.

After the correlations are developed for the above specified conditions, the effects of cuttings concentration, pipe eccentricity and pipe rotary speed are further analysed and discussed.

1. **Fluid lift coefficient \( C_L \) and particle Reynolds number \( N_{Rep} \)**

It is speculated that as the case for the correlation between \( C_D \) and \( N_{Rep} \) for particle settling velocity, the fluid lift coefficient \( C_L \) will mainly be a function of the particle Reynolds number \( N_{Rep} \) as well. In the following analysis, the calculation procedure for \( C_L \) and \( N_{Rep} \) and their correlation for cuttings suspension are presented.
a. Procedure for the calculations of $C_L$ and $N_{Rep}$

The calculation procedure for $C_L/N_{Rep}$ for cuttings suspension has been shown in Fig. 8.2.1. It can be summarised as follows:

- Use the fluid viscometer readings to calculate the fluid rheological properties so that the fluid rheological parameters can be obtained;
- Calculate the fluid velocity profile and fluid viscosity profile at the fluid velocity of MTV for cuttings suspension so that the fluid point velocity $v_p$ and the fluid effective viscosity $\mu_e$ approaching the centre of the cuttings resting on the low-side annular wall are derived;
- Compute the fluid lift coefficient $C_L$ using Eq. 8.2.2;
- Calculate the particle Reynolds number $N_{Rep}$ by Eq. 8.2.3.

b. The correlation of $C_L$ and $N_{Rep}$

Based on the experimental data of the MTV for cuttings suspension, a series of fluid lift coefficient $C_L$ and particle Reynolds number $N_{Rep}$ has been obtained, which is plotted in Fig. 8.2.2. Considering the complexity of cuttings transport process in deviated wells, the correlation between $C_L$ and $N_{Rep}$ seems to be very good. As the case of the correlation between $C_D$ and $N_{Rep}$ for cuttings settling velocity, a clear deviation of the curve occurs when the particle Reynolds number is above a certain value. From this figure, it can be seen that for a log-log co-ordinate system, the relationship between $C_L$ and $N_{Rep}$ is linear when the particle Reynolds number $N_{Rep}$ is less than 120.0 and $C_L$ becomes a constant of 0.031 while $N_{Rep}$ is greater than 120.0. Therefore, as the case for the correlation of $C_D$ and $N_{Rep}$ for particle settling velocity, a general correlation between $C_L$ and $N_{Rep}$ may be well represented by:

$$C_L = \frac{a}{N_{Re_p}^b} \quad (8.2.6)$$

Based on the experimental data in Fig. 8.2.2, $C_L$ and $N_{Rep}$ are correlated using regression analysis.

For laminar flow regime:
Define Input Parameters required
\( \Phi, d_1, d_2, \rho_f, d_s, \rho_s, \text{MTV}, \) Viscometer readings

The Force Balance MTV Model for cuttings suspension

Calculate \( n/K \): Curve-fitting of the viscometer readings

Compute \( v_p \): Fluid velocity profile

Calculate \( \mu_o \): Fluid viscosity profile

Compute: lift coefficient \( C_L \)

Calculate: Reynolds number \( N_{Rep} \)

Analyse data and correlate the relationship between \( C_L \) and \( N_{Rep} \)

Verify the model: Experiments + Field data

Experimental Data Base on the MTV

Classic concepts: \( C_L, N_{Rep} \)

Shear Stress

Shear Rate

Fluid Velocity

Radial Position

Fluid Viscosity

Radial Position

\[
C_L = \frac{3 \cdot d_s \left( \frac{\rho_s}{\rho_f} - 1.0 \right) \cdot g \cdot \sin(\Phi)}{4 \cdot v_p^2}
\]

\[
N_{Rep} = \frac{v_p \cdot d_s \cdot \rho_f}{\mu_o}
\]

LOG(C_L)

LOG(N_{Rep})

Final MTV model for cuttings suspension

Fig. 8.2.1 Flowchart for the development of the \( C_L \) and \( N_{Rep} \) correlation for cuttings suspension
\[ C_L = \frac{0.651}{N_{Re_p}^{0.63867}} \quad (N_{Re_p} \leq 120.0) \]  \hspace{1cm} (8.2.7)

and for turbulent flow regime:

\[ C_L = 0.031 \quad (N_{Re_p} > 120.0) \]  \hspace{1cm} (8.2.8)

Eqs. 8.2.7 and 8.2.8 are the MTV correlation for cuttings suspension, which are named as the MTV model for cuttings suspension because the MTV for cuttings suspension can be calculated using these two correlations.

(2) **Fluid drag coefficient \( C_D \) and particle Reynolds number \( N_{Re_p} \)**

a. **Calculation procedures of \( C_D \) and \( N_{Re_p} \)**

The calculation procedure for the fluid drag coefficient \( C_D \) and the particle Reynolds number \( N_{Re_p} \) for cuttings rolling is similar to that shown in Fig. 8.2.1 for the development of \( C_L/N_{Re_p} \) correlation for cuttings suspension. It is summarised as follows:

- Use the fluid viscometer readings to calculate the fluid rheogram so that the fluid rheological parameters can be determined;
- Calculate the annular flow profiles at the fluid velocity of MTV for cuttings rolling to obtain the fluid point velocity \( v_p \), the shear rate \( \gamma_{sp} \) and the effective viscosity \( \mu_e \) approaching the centre of the cuttings resting on the low-side annular wall;
- Compute the particle Reynolds number for cuttings suspension by Eq. 8.2.3 and then calculate the fluid lift coefficient \( C_L \) either by Eq. 8.2.7 or by Eq. 8.2.8 depending on the particle Reynolds number;
- Calculate the effective shear rate acting on the fluid around the cuttings based on Eqs. 8.2.5 and 7.1.10;
- Compute the effective viscosity of the fluid around the cuttings using Eq. 7.3.6;
- Compute the fluid lift coefficient \( C_D \) using Eq. 8.2.4;
- Calculate the particle Reynolds number \( N_{Re_p} \) for cuttings rolling by Eq. 8.2.3;
b. The correlation of $C_D$ and $N_{Rep}$ for cuttings rolling

Based on the experimental data for the MTV for cuttings rolling, a series of fluid drag coefficient $C_D$ and particle Reynolds number $N_{Rep}$ is calculated, which is plotted in Fig. 8.2.3. It can be seen that the relationship between $C_D$ and $N_{Rep}$ is very good indeed.

When the particle Reynolds number is below a certain value, the relationship between $C_D$ and $N_{Rep}$ is linear. However, when the particle Reynolds number is above a certain value, the relationship between $C_D$ and $N_{Rep}$ has becomes a constant.

For a log-log co-ordinate system, the relationship between $C_D/N_{Rep}$ is linear when the particle Reynolds number is below 15.5 and $C_D$ becomes a constant of 0.2153 while $N_{Rep}$ is greater than 15.5. Therefore, as the case for the correlation of $C_D$ and $N_{Rep}$ for particle settling velocity, the general correlation between $C_D$ and $N_{Rep}$ may be generalised as follows:

$$C_D = \frac{a}{N_{Rep}^b}$$  \hspace{1cm} (7.3.7)

Based on the experimental data in Fig. 8.2.3, $C_D$ and $N_{Rep}$ have been correlated using regression analysis.

For laminar flow regime:

$$C_D = \frac{3.016}{N_{Rep}^{0.96335}} \quad \quad (N_{Rep} \leq 15.5)$$  \hspace{1cm} (8.2.9)

and for turbulent floe regime:

$$C_D = 0.2153 \quad \quad (N_{Rep} > 15.5)$$  \hspace{1cm} (8.2.10)

Eqs. 8.2.9 and 8.2.10 are the MTV correlation for cuttings rolling, which are named as the MTV model for cuttings rolling because the MTV for cuttings rolling can be calculated using the two correlations.

Comparing Figs. 8.2.2 and 8.2.3, it can be seen that the correlation of $C_D/N_{Rep}$ for cuttings rolling is much better than that of $C_L/N_{Rep}$ for cuttings suspension. This may be caused by two reasons. One is for the fact that the initiation of cuttings rolling is easy to
Fig. 8.2.2 Relationship between the fluid lift coefficient $C_L$ and particle Reynolds number $N_{Rep}$ for cuttings suspension.

$$C_L = \frac{0.651}{N_{Rep}^{0.63867}}$$

Critical Reynolds number: $120$

$CL=0.031$

Fig. 8.2.3 Relationship between the fluid drag coefficient $C_D$ and particle Reynolds number $N_{Rep}$ for cuttings rolling.

$$C_D = \frac{3.016}{N_{Rep}^{0.96335}}$$

Critical Reynolds Number $N_{Re_p} = 15.5$

$C_D = 0.2135$
identify during the cuttings transport experiments. This made the experimental data for cuttings rolling more accurate. The other reason is that the effective viscosity for $C_D$ and $N_{Rep}$ for cuttings rolling has been better calculated than that for $C_L/N_{Rep}$ for cuttings suspension.

8.2.6 Prediction procedures for the MTV

The MTV models for both cutting suspension and cuttings rolling have been established in section 8.2.5. In this section, the detailed procedure for the predictions of the MTV for adequate deviated hole cleaning is presented.

To predict the MTV, a computer program needs to go through a series of iterations as illustrated in Fig. 8.2.4 for the predictions of the MTV for cuttings suspension.

First of all, an assumed annular fluid velocity $V_f$, the fluid rheological parameters and other drilling parameters are used to generate the fluid velocity profile and fluid viscosity profile.

The fluid point velocity $v_p$ and the effective viscosity $\mu_e$ are then used for the calculation of the particle Reynolds number $N_{Rep}$. Then, the fluid lift coefficient is calculated using Eq. 8.2.7 or Eq. 8.2.8 obtained in section 8.2.5. Thereafter a new point velocity $v_p'$ will be derived from the force balance models of the MTV. Based on the new point velocity $v_p'$, a new fluid velocity $V_f'$ needs to be calculated.

If the newly calculated fluid velocity $V_f'$ is nearly the same as the assumed fluid velocity $V_f$, $V_f$ will be MTV required for cuttings suspension. Otherwise, the newly calculated fluid velocity $V_f'$ will be taken as the assumed fluid velocity $V_f$. Another iteration starts until the MTV converges.

The prediction procedure for the MTV for cuttings rolling is similar to that shown in Fig 8.2.4 for cuttings suspension, details of which are not presented in the thesis.

Based on the above procedure, the MTV for both cuttings suspension and cuttings rolling are predicted for a given set of drilling parameters. In section 8.3, comparison between the experimental data and model predictions are made based on the present experiments. In
**Input Parameters required**

\( \Phi, d_1, d_2, \rho_f, d_s, \rho_s, r_{op}, \text{rpm}, E\% \),

Viscometer readings

**MTV Model**

for cuttings suspension

Calculate \( n/K \):
Curve-fitting of viscometer readings

Assume MTV = \( v_f \)

Compute \( v_p \):
Fluid velocity profile

Calculate \( \mu \_\phi \):
Fluid viscosity profile

Compute \( N_{Rep} \)
then calculate \( C_L \) using the correlation

Calculate:
new point velocity \( v_p' \)

\( v_p' = v_p \) ?

No

Yes

MTV = \( v_f \)

\[ v_p' = \sqrt{\frac{3 \cdot d_f \left( \frac{\rho_f - 1.0}{\rho_f} \right) \cdot g \cdot \sin(\Phi)}{4 \cdot C_L}} \]

Calculate \( v_f' \) for the given \( v_p' \)
using the annular flow equations, then let \( v_f = v_f' \)

**Fig. 8.2.4 Flowchart for the prediction procedure of MTV for cuttings suspension**
chapter 10, an extensive sensitivity analysis of the various drilling parameters on the MTV is presented including the effect of pipe eccentricity.

8.2.7 Extension of the MTV models

In the development of the MTV correlations in section 8.2.5, the MTV models have been limited into the following conditions:

- Cuttings concentration of 2% by volume;
- Concentric annuli without drill pipe rotation.

However, in actual drilling practices, the drill pipe may be rotated and it may also offset toward the borehole wall to become eccentric annuli. The rate of penetration may be varied in a wide range as well. In order to expand the applicability of the present study, these effects need to be analysed so that the MTV for deviated hole cleaning can be predicted at more realistic conditions.

(1) Effect of cuttings concentration on the MTV

Cuttings concentration i.e. rate of penetration is one of the few controllable parameters during drilling operations. Its effect on the MTV for deviated hole cleaning has been discussed in section 5.5.8, which showed that cuttings concentration does affect deviated hole cleaning efficiency. Therefore, to have a better understanding of the effect of cuttings concentration on the MTV is very important. In this section, the effect of cuttings concentration on the MTV is analysed purely based on the experimental results and then its effect on the MTV is correlated using empirical method.

In chapters 4 & 5, it has been known that four different cuttings concentrations have been used during the present cuttings transport experiments including 1%, 2%, 3% and 4% by volume. In order to incorporate the effect of cuttings concentration into the MTV models developed in section 8.2.5, these experimental data are analysed so that an empirical correction factor correlation is obtained for the MTV model respectively for cuttings suspension and for cuttings rolling. The detailed procedure is presented as follows:
Corresponding to each set of the experimental parameters at the cuttings concentration of 1%, 3% and 4% by volume, use the MTV models to predict the MTV for both cuttings suspension and cuttings rolling, which in fact are the MTV at 2% by volume of cuttings concentration. The predicted MTV is expressed as MTV@2%, which means the MTV at 2% cuttings concentration;

- Divide the experimentally measured MTV, which is expressed as MTV@C_s% which means the MTV at the cuttings concentration of C_s% by volume for cuttings suspension and cuttings rolling respectively, by the predicted MTV at 2% by volume of cuttings concentration;

- The average ratio of MTV@C_s%/MTV@2% for each of the cuttings concentration by volume percentage was obtained for the MTV respectively for cuttings suspension and for cuttings rolling;

- The average ratio at each of the cuttings concentration against the cuttings volume percentage is plotted respectively for cuttings suspension and for cuttings rolling, which has been respectively shown in Fig. 8.2.5 and in Fig. 8.2.7.

- Then, correlate the relationship between the ratio of MTV@C_s%/MTV@2% and the cuttings concentration percentage by volume respectively for cuttings suspension and for cuttings rolling.

Fig. 8.2.5 shows the relationship between the ratio of MTV@C_s%/MTV@2% and the cuttings concentration for cuttings suspension. It can be easily seen that as the cuttings concentration increases, the ratio of MTV@C_s%/MTV@2% increases until 3% cuttings concentration is reached. Then, with a further increase in the cuttings concentration, the ratio decreases shapely. This means that if the cuttings concentration is below 3%, the MTV will be increased with an increase in cuttings concentration. However, when the cuttings concentration is above 3% by volume, with a further increase in the cuttings concentration, the MTV will be reduced i.e. hole cleaning will be improved.

As we know that except for using the concept of the MTV for efficient hole cleaning analysis, the cuttings concentration in the annulus is also a useful factor to be considered while evaluating cuttings transport efficiency. It is very clear that the higher the cuttings
concentration in the annulus, the more likely hole cleaning problems may occur. Though
the MTV will be reduced when the cuttings concentration is above 3%, the overall load of
the cuttings in the annulus will be much increased. Therefore, from the conservative point
of view, in the correction factor correlation for the effect of cuttings concentration on the
MTV, a constant ratio of MTV@C$_s$%/MTV@2% at the level of 3% is set when the cuttings
concentration is above 3% by volume.

Based on the above discussion, the correlation factor for the effect of cuttings concentration
on cuttings suspension has been obtained as:

\[
\frac{MTV@C_s}{MTV@2\%} = 0.6207 + 0.18965 \cdot C_s\% \quad (C_s \leq 3\%) \quad (8.2.11)
\]

and

\[
\frac{MTV@C_s}{MTV@2\%} = 1.18965 \quad (C_s > 3\%) \quad (8.2.12)
\]

Eq. 8.2.11 shows that when the cuttings concentration is 2% by volume, the correction
factor of MTV@C$_s$%/MTV@2% is 1.0 which is exactly the case in practice.

Fig. 8.2.7 shows that the effect of cuttings concentration on the MTV for cuttings rolling is
quite the same as that for cuttings suspension. As the cuttings concentration is below 3%,
with an increase in cuttings concentration, the ratio of MTV@C$_s$%/MTV@2% increases.
When the cuttings concentration is above 3%, this ratio drops sharply, which means that as
the cuttings concentration is below 3%, the MTV increases with an increase in cuttings
concentration. However, as the cuttings concentration is above 3%, the MTV decreases as
the cuttings concentration increases.

Following the similar treatment as the case for cuttings suspension, when the cuttings
concentration is above 3%, a constant ratio of MTV@C$_s$%/MTV@2% at the level of 3%
cuttings concentration is taken from the conservative point of view. Based on the
discussion presented, the correction factor for the effect of cuttings concentration on
cuttings rolling has been found to be:

\[
\frac{MTV@C_s}{MTV@2\%} = 0.442 + 0.279 \cdot C_s\% \quad (C_s \leq 3\%) \quad (8.2.13)
\]

and
As can be seen from Eq. 8.2.13 when the cuttings concentration is 2% by volume, the correction factor of \( \frac{\text{MTV}@C_s\%}{\text{MTV}@2\%} \) is 1.0 which further validates the correlations.

It is interesting to find that the present correlation for the effect of cuttings concentration on the MTV for cuttings suspension is quite the same as that developed by Luo et al\(^{(72)}\). The comparison of the effect of cuttings concentration on the MTV for cuttings suspension between Luo et al' correlation and the present correlation has been plotted in Fig. 8.2.9.

From Fig. 8.2.9, it can be seen that as the cuttings concentration is below 3%, there is virtually no difference between the present correlation and that by Luo et al\(^{(72)}\). However, Luo et al' correlation follows the linear relationship for any cuttings concentration. But, based on the present experiments, the effect of cuttings concentration on the MTV drops when the cuttings concentration is above 3%. However, from the conservative point of view, a constant was purposely set when the cuttings concentration is above 3% in the present correlation.

In summary, the effect of cuttings concentration on the MTV for both cuttings rolling and cuttings suspension has been correlated. Therefore, the MTV for any rate of penetration can now be predicted following the procedure of:

- Predict the MTV at 2% cuttings concentration using the procedure presented in section 8.2.6.
- Correct the MTV at the actual cuttings concentration or rate of penetration using the correlations developed in the present section.

(2) Effect of pipe eccentricity and pipe rotary speed

The experiments presented in section 5.5.6 showed that pipe eccentricity has significant effect on the MTV for both cuttings rolling and cuttings suspension. In this section, following the same principle and using the same source codes as those discussed in section 7.5.1 for the eccentric annular flow with/without pipe rotation and concentric annular flow
Fig. 8.2.5 Effect of cuttings concentration on the MTV for cuttings suspension

Fig. 8.2.6 Correlation for the effect of cuttings concentration on the MTV for cuttings suspension
Fig. 8.2.7 Effect of cuttings concentration on the MTV for cuttings rolling

Fig. 8.2.8 Correlation for the effect of cuttings concentration on the MTV for cuttings rolling

Fig. 8.2.9 Comparison of the effect of cuttings concentration on the MTV for cuttings suspension between the present correlation and that by Luo et al (72)
with pipe rotation, the present MTV models are extended so that the effect of pipe eccentricity and pipe rotary speed can be analysed and predicted.

From the development of the present MTV models, it has been clearly seen that direct force balance has been used to describe the initiation of the cuttings movement in a deviated wellbore, the beauty of which is that as long as the fluid velocity profile and fluid viscosity profile in the annulus can be predicted, the MTV at this geometry can then be calculated quite accurately.

As the case for the calculations of the MTV for vertical hole cleaning, the criterion for the MTV calculations should be based on the cuttings resting on the low-side annular wall. In this case, the fluid velocity and viscosity at the biggest annular clearance should be used when the eccentricity is negative. If the pipe eccentricity is positive, the fluid point velocity and viscosity should be calculated for the smallest annular clearance. Concerning the annular flow calculations, the same program as discussed in section 7.5.1 has been used. Similar to the MTV predictions for vertical hole cleaning, the MTV for both cuttings rolling and cuttings suspension required for deviated hole cleaning can be calculated for eccentric annuli with/without pipe rotation. An extensive analysis of the various drilling parameters on the MTV for deviated hole cleaning including the effect of pipe eccentricity and pipe rotary speed are presented in chapter 10.

8.3 Verification of the newly proposed MTV models

In section 8.2, two MTV models describing the minimum transport velocity required for adequate deviated hole cleaning have been developed. In this section, a comparison between the experimental data and the model predictions is made so that the newly proposed MTV models are validated. The models are also used to analyse some of the field data from the North Sea.

8.3.1 Comparison between model predictions and the experimental data

To verify the MTV models, the most obvious approach is to compare the experimental data against the model predictions. Based on the solution procedures for the MTV predictions,
the MTV models are used to predict the MTV corresponding to each of the experimental conditions. Then, the measured MTV against the predicted MTV are plotted in Fig. 8.3.1 for cuttings suspension and in Fig. 8.3.2 for cuttings rolling.

From Figs. 8.3.1 and 8.3.2, it can be seen that in general, the new models are shown to be representative of the experimental data. If the relative error is being evaluated by Eq. 7.4.1, the average error of the entire population of results for the MTV for cuttings suspension is 18.8% whilst the average error of the entire population of results for the MTV for cuttings rolling is 23.6%. Hence we can assume that the models represent the transport process simulated and observed in the laboratory. However, it is worth examining the conditions under which the models deviate from the experimental data. The differences between the model predictions and the experimental data are expressed as a function of the major parameters affecting the MTV. These comparisons are shown in Tables 8.3.1 to 8.3.4.

Table 8.3.1 shows that the greatest error for both cuttings suspension and cuttings rolling occurs at 90° hole angle. In fact, for the case of MTV for cuttings suspension, the measured MTV drops down at 90° hole angle. However, based on the model prediction, the MTV for cuttings suspension should be maximum at 90°. Efforts have been made to try to identify the mechanisms for this phenomenon. But, no satisfactory conclusions have been derived, which needs further investigation. For the MTV for cuttings rolling, a very thick cuttings moving bed is often observed at 90° during the experiments, which often results in very low MTV for cuttings rolling, which the MTV model can not predict satisfactorily.

From Tables 8.3.2 to 8.3.4, it can be seen that the major differences in the model predictions and the experimental data occur in experiments conducted in the large annulus, when using very viscous fluids and small cuttings. This will result in low values of particle Reynolds number $N_{Rep}$ and as discussed above, the correlations between $C_D$ and $N_{Rep}$ and between $C_L$ and $N_{Rep}$ tend to degenerate at very low values of $N_{Rep}$. Fortunately, when very viscous fluid is used to transport very small cuttings, the MTV for both cuttings suspension and cuttings rolling is very low so that we are less concerned.
Fig. 8.3.1 Comparison of the predicted MTV and the measured MTV for cuttings suspension

Fig. 8.3.2 Comparison of the predicted MTV and the measured MTV for cuttings rolling
Table 8.3.1  Model prediction error for the MTV as a function of hole angle

<table>
<thead>
<tr>
<th>Hole Angle</th>
<th>Suspension</th>
<th></th>
<th>Rolling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees</td>
<td>% error</td>
<td>Data Points</td>
<td>% error</td>
</tr>
<tr>
<td>90</td>
<td>32.4</td>
<td>28</td>
<td>30.5</td>
</tr>
<tr>
<td>75</td>
<td>10.2</td>
<td>5</td>
<td>14.8</td>
</tr>
<tr>
<td>60</td>
<td>12.1</td>
<td>16</td>
<td>15.6</td>
</tr>
<tr>
<td>50</td>
<td>10.4</td>
<td>23</td>
<td>21.1</td>
</tr>
<tr>
<td>40</td>
<td>11.5</td>
<td>20</td>
<td>21.3</td>
</tr>
<tr>
<td>30</td>
<td>20.1</td>
<td>24</td>
<td>26.9</td>
</tr>
<tr>
<td>15</td>
<td>26.9</td>
<td>10</td>
<td>25.9</td>
</tr>
<tr>
<td>0</td>
<td>18.6</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

Table 8.3.2  Model prediction error for the MTV as a function of fluid rheology

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Suspension</th>
<th></th>
<th>Rolling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% error</td>
<td>Data Points</td>
<td>% error</td>
</tr>
<tr>
<td>k&lt;5</td>
<td>19.5</td>
<td>25</td>
<td>16.8</td>
</tr>
<tr>
<td>5&lt;k&lt;20</td>
<td>18.4</td>
<td>54</td>
<td>14.8</td>
</tr>
<tr>
<td>k&gt;20</td>
<td>18.9</td>
<td>78</td>
<td>30.8</td>
</tr>
</tbody>
</table>
Table 8.3.3 Model prediction error for the MTV as a function of the annular size

<table>
<thead>
<tr>
<th>Annular Size</th>
<th>Suspension</th>
<th></th>
<th>Rolling</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% error</td>
<td>Data Points</td>
<td>% error</td>
<td>Data Points</td>
</tr>
<tr>
<td>13.7 x 8.89</td>
<td>18.0</td>
<td>23</td>
<td>26.0</td>
<td>19</td>
</tr>
<tr>
<td>13.7 x 6.10</td>
<td>17.3</td>
<td>119</td>
<td>18.8</td>
<td>96</td>
</tr>
<tr>
<td>13.7 x 3.34</td>
<td>32.1</td>
<td>15</td>
<td>40.9</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 8.3.4 Model prediction error for the MTV as a function of cuttings size

<table>
<thead>
<tr>
<th>Particle Size cm</th>
<th>Suspension</th>
<th></th>
<th>Rolling</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% error</td>
<td>Data Points</td>
<td>% error</td>
<td>Data Points</td>
</tr>
<tr>
<td>0.28</td>
<td>19.9</td>
<td>26</td>
<td>12.8</td>
<td>21</td>
</tr>
<tr>
<td>0.18</td>
<td>16.5</td>
<td>124</td>
<td>21.0</td>
<td>98</td>
</tr>
<tr>
<td>0.14</td>
<td>18.4</td>
<td>5</td>
<td>32.8</td>
<td>5</td>
</tr>
<tr>
<td>0.084</td>
<td>24.3</td>
<td>12</td>
<td>52.4</td>
<td>15</td>
</tr>
</tbody>
</table>
8.3.2 Comparison between model predictions and field data

An attempt at validating the MTV models using field data has been made. The MTV models are used to calculate the MTV required to ensure cuttings transport in both cuttings rolling and cuttings suspension for field data supplied by the project sponsors. The detailed operating parameters are tabulated in Table 8.3.5. In the analysis, the MTV and consequent flow rate requirements for the various drilling conditions have been calculated for concentric annuli without pipe rotation and are compared with the actual flow rate used during the respective operations, which has been shown in Table 8.3.6.

Before further discussions, it needs to be pointed out that during the present study, an effort has been made to collect more field data, especially for those wells with hole cleaning problems. But, it was not successful. No project sponsors have provided the detailed information requested such as high torque and other indicators for poor hole cleaning. Therefore, this has made it extremely difficult for the author to access the models accurately. However, the project sponsors have made some comments on hole cleaning related problems. It was observed that in some cases, hole cleaning was very poor without pipe rotation. Their experience is that without pipe rotation, there were no cuttings recovered at the shaker. However, as soon as the pipe was rotated, a reasonable quantity of cuttings were recovered.

Table 8.3.6 shows that for small hole sizes (8.5" hole), the field operating flow rates are higher than the flow rates required for cuttings suspension and are much higher than the flow rates required for cuttings rolling. This means that for small hole diameters, hole cleaning is dominated by cuttings suspension in actual practice i.e. the hole is usually perfectly cleaned. That may lead to the conclusion that hole cleaning should not be a problem for the wells with small hole diameters, which is in agreement with field experience. As a matter of fact, during the drilling operations for the 8.5" holes, the actual pump rates can be further reduced in order that the drilling hydraulics can be most effectively utilised.
Table 8.3.5 Summary of the field data supplied by the project sponsors

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
<th>M10</th>
<th>M11</th>
<th>M12</th>
<th>EE3</th>
<th>N1</th>
<th>N1/15/1</th>
<th>N1/15/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Angle (degrees)</td>
<td>54</td>
<td>52</td>
<td>52</td>
<td>48</td>
<td>41</td>
<td>46</td>
<td>47</td>
<td>48</td>
<td>17</td>
<td>16</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Annular Size (inch)</td>
<td>17.5 x 5</td>
<td>12.25 x 5</td>
<td>12.25 x 5</td>
<td>12.25 x 5</td>
<td>8.5 x 5</td>
<td>8.5 x 5</td>
<td>8.5 x 5</td>
<td>8.5 x 5</td>
<td>27.41 x 5</td>
<td>16 x 6.63</td>
<td>16 x 6.63</td>
<td></td>
</tr>
<tr>
<td>Cuttings size: mm</td>
<td>0.296</td>
<td>1.12</td>
<td>1.35</td>
<td>0.757</td>
<td>0.592</td>
<td>0.33</td>
<td>0.707</td>
<td>0.393</td>
<td>2.54</td>
<td>3.155</td>
<td>0.82</td>
<td>0.59</td>
</tr>
<tr>
<td>Mud Type</td>
<td>WBM</td>
<td>OBM</td>
<td>OBM</td>
<td>OBM</td>
<td>OBM</td>
<td>OBM</td>
<td>OBM</td>
<td>OBM</td>
<td>OBM</td>
<td>OBM</td>
<td>LTOBM</td>
<td>LTOBM</td>
</tr>
<tr>
<td>Mud density: ppg</td>
<td>9.2</td>
<td>9</td>
<td>8.9</td>
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Table 8.3.6: MTV predictions for field data provided by sponsoring companies.
For large hole sizes i.e. 12.25", 16" or 17.5" hole diameter, the MTV for cuttings suspension can hardly be achieved. The actual flow rates are usually well below the flow rates required for cuttings suspension, especially for 16" and 17.5" hole diameters, which can be seen from Table 8.3.6 for the sample No. N1, M5 etc. However, in most of the cases, the flow rates required for cuttings rolling are achieved, which can be seen for sample No. N1/15/1, M5, N1/15/2 etc. In some other cases, even the flow rates required for cuttings rolling can’t be achieved in actual practice as shown for the sample No. N2/23/1, N2/23/2, N2/23/3, N1 etc. In these situations, a stationary cuttings bed will be formed on the low-side annular wall. Here, it needs to be realised that the above calculations are based on concentric annuli without pipe rotation. Obviously some hole cleaning problems may be experienced if the drill pipe is not rotated. This seems to be in agreement with the field experience that quite often while drilling with large drill bits, no cuttings can be recovered without pipe rotation. However, as soon as the pipe is rotated, significant improvement can be observed. This is because without pipe rotation, the flow rates required for cuttings rolling and cuttings suspension can’t be achieved. However, with pipe rotation, especially considering the pipe orbital motion, the flow rates required for cuttings rolling can be significantly reduced i.e. a better hole cleaning can be obtained.

It also needs to be pointed out that the predicted MTV is the fluid velocity required to remove the cuttings resting on the low-side annular wall, where the cuttings are most difficult to be cleaned out of the borehole. As is discussed in chapter 10 for the effect of cuttings radial positions on the MTV, when the cuttings approach the central region of the annulus are considered, the predicted MTV will be significantly reduced i.e. in actual practice, there may be a very thin stationary cuttings bed in the annulus. Above the bed, all the cuttings can be transported up to the surface.

Since we are aware that hole angle, annular size and fluid rheology all have a significant effect on the MTV, the impact of these parameters on the predicted MTV is investigated for some of the field data. It can be seen from Table 8.3.7 that the MTV for rolling or suspension opposite the BHA for the 16" and 12 1/4" hole is not significantly different from that opposite the drill pipe.
Table 8.3.7: Predicted MTV versus actual flowrate in BHA sections

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<td>N3/24/2</td>
<td>50</td>
<td>16</td>
<td>8</td>
<td>0.354</td>
<td>269</td>
<td>353</td>
<td>2333</td>
</tr>
<tr>
<td>N2/23/1</td>
<td>30</td>
<td>16</td>
<td>6.625</td>
<td>0.302</td>
<td>252</td>
<td>284</td>
<td>2182</td>
</tr>
<tr>
<td>N2/23/2</td>
<td>48</td>
<td>16</td>
<td>6.625</td>
<td>0.156</td>
<td>181</td>
<td>352</td>
<td>1567</td>
</tr>
<tr>
<td>N2/23/3</td>
<td>58</td>
<td>12.25</td>
<td>6.625</td>
<td>0.347</td>
<td>307</td>
<td>354</td>
<td>1332</td>
</tr>
<tr>
<td>N2/23/5</td>
<td>56</td>
<td>12.25</td>
<td>6.625</td>
<td>0.283</td>
<td>266</td>
<td>313</td>
<td>1154</td>
</tr>
<tr>
<td>N3/24/1</td>
<td>27</td>
<td>16</td>
<td>6.625</td>
<td>0.309</td>
<td>281</td>
<td>294</td>
<td>2433</td>
</tr>
<tr>
<td>N3/24/2</td>
<td>50</td>
<td>16</td>
<td>6.625</td>
<td>0.354</td>
<td>268</td>
<td>357</td>
<td>2321</td>
</tr>
</tbody>
</table>
Table 8.3.8 demonstrates that in 16'' holes the MTV required for hole angles up to 10 degrees is close to or less than the actual pumping rates used. In the 12.25'' hole section, the MTV requirements are within the actual pumping rates at angles of 20 to 30 degrees but are much higher than the actual rates above these angles.

The other variable which has a significant effect on the MTV is the rheological nature of the fluids. Table 8.3.9 shows the impact of fluid rheology on the MTV using the fluid in one of the 17.5'' hole sections of the M4 well. If this fluid is used in the N wells, the MTV is significantly lower and in most cases within the actual pumping rates used. This point illustrates the functionality of the computer program in terms of sensitivity analysis which is discussed in chapter 10.

8.4 Comparison between the present model and the models by other researchers

Two models have been reported in the literature, which have used the similar concepts to the present MTV to define deviated hole cleaning. One model is developed by Luo et al, which describes the flow rate for cleaning deviated wells using the same concept as the present MTV for cuttings suspension. The other model is reported by Larsen et al, which predicts the minimum fluid velocity \( v_{\text{crit}} \) to maintain a continuously upward movement of the cuttings, which may in fact correspond to the present MTV for cuttings rolling. Due to the similarities of these concepts for the predictions of hole cleaning efficiency, a detailed discussion is presented for the experimental facilities, the model predictions, and the various conclusions derived based on the different studies.

8.4.1 Comparison of the experimental facilities and experimental parameters

Due to the fact that all the cuttings transport models are established based on laboratory experimental data, it will be useful to analyse the experimental facilities and experimental parameters used by the different researchers before making the comparison of the different model predictions. The comparison of the experimental facilities and experimental parameters of the different researchers have been tabulated in Table 8.4.1.
Table 8.3.8: Effect of hole angle on the MTV for some of the field data

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Hole Angle</th>
<th>Hole Size</th>
<th>BHA OD</th>
<th>Cuttings Size</th>
<th>Predicted MTV, ft/min</th>
<th>Predicted Flowrate, gpm</th>
<th>Actual Flow, gpm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rolling</td>
<td>Suspension</td>
<td>Rolling</td>
</tr>
<tr>
<td>N3/24/2</td>
<td>5</td>
<td>16</td>
<td>6.625</td>
<td>0.354</td>
<td>199</td>
<td>75</td>
<td>1720</td>
</tr>
<tr>
<td>N3/24/2</td>
<td>10</td>
<td>16</td>
<td>6.625</td>
<td>0.354</td>
<td>227</td>
<td>122</td>
<td>1966</td>
</tr>
<tr>
<td>N3/24/2</td>
<td>20</td>
<td>16</td>
<td>6.625</td>
<td>0.354</td>
<td>253</td>
<td>216</td>
<td>2187</td>
</tr>
<tr>
<td>N3/24/2</td>
<td>30</td>
<td>16</td>
<td>6.625</td>
<td>0.354</td>
<td>265</td>
<td>306</td>
<td>2293</td>
</tr>
<tr>
<td>N3/24/5</td>
<td>5</td>
<td>12.25</td>
<td>6.625</td>
<td>0.361</td>
<td>232</td>
<td>45</td>
<td>1007</td>
</tr>
<tr>
<td>N3/24/5</td>
<td>10</td>
<td>12.25</td>
<td>6.625</td>
<td>0.361</td>
<td>246</td>
<td>90</td>
<td>1068</td>
</tr>
<tr>
<td>N3/24/5</td>
<td>20</td>
<td>12.25</td>
<td>6.625</td>
<td>0.361</td>
<td>271</td>
<td>178</td>
<td>1176</td>
</tr>
<tr>
<td>N3/24/5</td>
<td>30</td>
<td>12.25</td>
<td>6.625</td>
<td>0.361</td>
<td>292</td>
<td>234</td>
<td>1267</td>
</tr>
<tr>
<td>N3/24/5</td>
<td>40</td>
<td>12.25</td>
<td>6.625</td>
<td>0.361</td>
<td>320</td>
<td>276</td>
<td>1389</td>
</tr>
<tr>
<td>N3/24/5</td>
<td>50</td>
<td>12.25</td>
<td>6.625</td>
<td>0.361</td>
<td>323</td>
<td>312</td>
<td>1402</td>
</tr>
</tbody>
</table>
Table 8.3.9: Effect of fluid rheology on the MTV using N Well conditions with M4 fluid

<table>
<thead>
<tr>
<th>Sample No</th>
<th>HOLE SIZE</th>
<th>MTV, ft/min</th>
<th>FLOW RATE, gpm</th>
<th>FIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rolling</td>
<td>Suspension</td>
<td>Rolling</td>
</tr>
<tr>
<td>N2/23/1</td>
<td>16</td>
<td>82</td>
<td>135</td>
<td>706</td>
</tr>
<tr>
<td>N2/23/2</td>
<td>16</td>
<td>4</td>
<td>191</td>
<td>34</td>
</tr>
<tr>
<td>N2/23/3</td>
<td>12.25</td>
<td>94</td>
<td>183</td>
<td>410</td>
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<tr>
<td>N2/23/4</td>
<td>12.25</td>
<td>0</td>
<td>88</td>
<td>0</td>
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<tr>
<td>N3/24/1</td>
<td>12.25</td>
<td>114</td>
<td>147</td>
<td>496</td>
</tr>
<tr>
<td>N3/24/2</td>
<td>16</td>
<td>138</td>
<td>226</td>
<td>1193</td>
</tr>
<tr>
<td>N4/14/1</td>
<td>16</td>
<td>156</td>
<td>173</td>
<td>1347</td>
</tr>
</tbody>
</table>
Table 8.4.1  Comparison of the experimental facilities and parameters between the present study and Luo et al' and Larsen et al' work

<table>
<thead>
<tr>
<th></th>
<th>Present Study</th>
<th>Luo et al(^{(72)})</th>
<th>Larsen et al(^{(85)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annular size:</td>
<td>13.7 x 3.34/6.10/8.89 cm</td>
<td>20.32 x 12.7 cm</td>
<td>12.7 x 6.03 cm</td>
</tr>
<tr>
<td>Annular length (ft.):</td>
<td>22</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>Hole angle (degrees):</td>
<td>0-90</td>
<td>0-90</td>
<td>55-90</td>
</tr>
<tr>
<td>Rotary speed (rpm):</td>
<td>0-200</td>
<td>0-200</td>
<td>0-150</td>
</tr>
<tr>
<td>Orbital rate of drillpipe</td>
<td>0-200</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Cuttings size (cm):</td>
<td>0.15--0.38</td>
<td>0.3 - 0.6</td>
<td>0.229, 0.445, 0.699</td>
</tr>
<tr>
<td>Cuttings con. (volume):</td>
<td>1-4%</td>
<td>1.5%+?</td>
<td>ROP=27, 54 &amp; 81 ft/hr</td>
</tr>
<tr>
<td>Fluids used:</td>
<td>CMC, Xc, Water, Bentonite, Poly Vis</td>
<td>CMC, Xc, Water, Bentonite</td>
<td>Water based</td>
</tr>
<tr>
<td>Fluid density (g/cm(^3)):</td>
<td>1.0--1.20</td>
<td>1.0-1.49</td>
<td>1.028-1.799</td>
</tr>
<tr>
<td>Eccentricity (%)</td>
<td>0.30, +50, -50, 70</td>
<td>0+?</td>
<td>-62 to + 62</td>
</tr>
</tbody>
</table>
Comparing with both Luo et al' and Larsen et al' work, the following particulars about the present studies can be found that:

- Three different annular sizes have been used by the present author so that the effect of annular size on the MTV has been more fully investigated.
- Four cuttings concentrations have been experimentally studied.
- A wider range of different fluid rheological properties have been tested, including the fluid by using mixed metal hydroxide (polyvis), which is extremely shear thinning.

It is clear that the present experimental programme is more extensive than the other two parties(72,85).

8.4.2 Comparison of the fundamentals of the different models

In section 2.5.2, it has been known that Luo et al(72) have used dimensional analysis to derive the various dimensionless groups. Then, the different dimensionless groups were correlated based on the experimental data. It is also seen that Larsen et al(85)'s model has little physical meaning and it was derived in the way without any physical significance in the view of the present author. However, the present MTV models are derived purely based on the analysis of the forces acting on the cuttings resting on the low-side annular wall. Two classic concepts have been directly used in the model correlations including the fluid drag force and fluid lift force. It is regarded by the present author that the present approach is more fundamental than the other two methods(72,85).

8.4.3 Comparison of the simulated results from the different models

Luo et al' paper(72), gives an example to illustrate the effect of hole angle and various other parameters on hole cleaning efficiency. Luo et al' example was based the following simulated conditions:

Annular size: 21.59 x 12.7 cm;
Hole angle: 60°;
Cuttings properties:
Size: 0.2 cm;
Penetration rate: 20 m/hr.;
Density: 2.60.

Fluid properties:
Type: Power law;
Rheologies: n=0.7 & K=300 eq. cp;
Density: 1.45 s.g.
Eccentricity: 0%;
Pipe rotary speed: 0 rpm;

Based on the above simulated drilling conditions, the MTV for both cuttings rolling and cuttings suspension have been calculated using the present MTV models. The results of these simulations are shown in Fig. 8.4.1 together with Luo et al' model predictions. The two curves for cuttings rolling and cuttings suspension are the predictions by the present models. The other curve is the predictions by Luo et al(72). It can be seen that the predictions of the present MTV models are in a well agreement with the predictions by Luo et al. It is interesting to note that Luo et al' predictions are quite close to the MTV for cuttings rolling. The predictions by Luo et al are somewhere in between the MTV for rolling and the MTV for cuttings suspension.

Also based on the above simulated conditions, the effect of fluid consistency index K on the MTV for both cuttings rolling and cuttings suspension has been predicted, which has been shown in Fig. 8.4.2. It can be easily seen that the predicted effect has exactly the same trend as that by Luo et al(72). This further validates the present MTV models.

Fig. 8.4.3 shows the comparison between Larsen et al' model predictions and the present model predictions. It is interesting to note that Larsen et al' predictions are quite close to the MTV for cuttings suspension. It can also be seen that the two models are also in a good agreement.

It is also interesting to note that the present models have in fact covered both the model by Luo et al and the model by Larsen et al.
Fig. 8.4.1 Comparison of the present model predictions against that by Luo et al(72)

Fig. 8.4.2 Predicted effect of consistency index on the MTV using Luo et al'(72) conditions

Fig. 8.4.3 Comparison of the present model predictions against that by Larsen et al(85)
8.4.4 Limitations of the different models

Due to the so many uncertainties of the problems we are dealing with, no model is a universal model i.e. all the models have their own limitations. In this section, the limitations of the various cuttings transport models are briefly discussed.

Luo et al's model has the following limitations:

Concentric annuli without pipe rotation.

Larsen et al' model is confined into:

Hole angles above 55°.

However, the present models not only can predict the MTV at eccentric annuli with pipe rotation, it can also be used to predict the effect of drill pipe orbital motion. The above discussion shows that the present models are more extensive than those by the previous researchers.

8.4.5 Discussion

Some of the statements in Luo et al(72)' paper and in Larsen et al(85)' paper do not comply with our experimental observations and results, which are briefly discussed.

a. The concept of the critical fluid velocity

The present author has defined two MTVs for deviated hole cleaning efficiency. One is the MTV for cuttings rolling and the other is the MTV for cuttings suspension. Luo et al(72) have only reported the MTV for cuttings suspension. The model reported by Larsen et al(85) is the minimum transport fluid velocity required to keep the upward movement of all the cuttings in the annulus. The cuttings transport mechanism was not specified, which is regarded to correspond to the present MTV for cuttings rolling. Therefore, the present MTV models are in fact the combination of Luo et al(72) model and Larsen et al(85) model.
b. Effect of annular size

Three annular sizes have been used in the present experiments. This has allowed us to evaluate the effect of annular size on the MTV based on laboratory data, which showed to be significant. Using these data, the effect of annular size was evaluated and the results were then extended into other annular sizes used in the field. It appears that Luo et al(72) have only used one annular size in the laboratory and the effect of annular size on the MTV was then evaluated using field data. Given the problems associated with the use of field data, we would consider this approach to be questionable. Larsen et al(85) has used only one annular size as well.

c. Effect of pipe eccentricity

The effect of pipe eccentricity has been investigated in the present studies, which showed to have a significant effect on the transport process. However, Luo et al(72) suggested that the effects of pipe eccentricity on the MTV are not significant enough to warrant inclusion in their model. Larsen et al(85) did not discuss the effect of pipe eccentricity on the critical transport velocity and the effect was not incorporated in their model either.

d. Effect of hole angle

The model reported by Luo et al(72) has only been used to predict the MTV from $30^\circ$ and above. For the hole angles of $0^\circ$-$30^\circ$, the MTV has been linearly interpolated based on the predicted critical flow rate at 30 degrees and that predicted for vertical wells. Furthermore the predicted critical flow rate for vertical wells has been on the basis of particle settling velocity model established for static fluids. Based on our experimental data, the effect of hole angle is not linear from 0 to 30 degrees and its effect is significant at low hole angles. The MTV for vertical wells has been predicted by the present author using a new cuttings settling velocity model for particle settling in dynamic non-Newtonian drilling fluids. Larsen et al(85)' model is only valid for highly deviated wellbores from $55^\circ$ to $90^\circ$, which is extremely limited.
e. **Effect of cuttings size**

Larsen et al\(^{85}\) concluded that smaller cuttings require a higher flow rate to be cleaned than the big cuttings. However, the present experiments showed that either big cuttings or small cuttings may be easier to be transported depending on the different drilling situations. Generally speaking, small cuttings are easier to be cleaned out of the borehole than the big cuttings.

f. **Effect of fluid viscosity**

The effect of fluid rheological properties is complicated in nature. Depending on the level of the viscosity and the size of the borehole geometry, either high viscosity or low viscosity may provide the most efficient cuttings transport. However, Larsen et al\(^{85}\) made a generalised conclusion that low viscosity fluid is more efficient than high viscosity fluids in deviated hole cleaning.

g. **Effect of pipe axial rotary speed**

Both Luo et al\(^{72}\) and Larsen et al\(^{85}\) concluded that pipe axial rotary speed has negligible effect on deviated hole cleaning. But, the present experiments showed that depending on the annular geometry and fluid properties, pipe axial rotation may have significant effect on the cuttings transport in both vertical and deviated wells.

8.5 **Discussions**

8.5.1 **Fluid shear stress versus hole cleaning efficiency**

Chin has published several papers\(^{29,30}\) for the investigation into drilled cuttings transport which stressed the importance of fluid shear stress on the low side annular wall to deviated hole cleaning efficiency. It was pointed out in one of his newly published papers that *it is the average shear stress acting on the low-side annular wall which is important to cuttings transport efficiency in deviated wells*, which is to be discussed in the present section.
As a matter of fact, the importance of fluid flow characteristics on particle transport has long been recognised. In the studies on hydraulic transport through circular pipes\(^{(37,38,50-55)}\) and sediment transport through open channels\(^{(64)}\), shear stress has been successfully used to model the transport capability of particles of different fluids.

In order to demonstrate the effect of fluid shear stress on deviated hole cleaning efficiency, some selective experiments have been used to calculate the shear stresses acting on the low side wall corresponding to each of the MTV, which is shown in Table 8.5.1 for some similar fluids and in Table 8.5.2 for some significantly different fluids.

It can be seen from Table 8.5.1 that for similar fluids, the required shear stresses to remove the same cuttings are quite the same i.e. shear stress does indicate hole cleaning efficiency.

Table 8.5.2 shows that for distinctly different fluids (Fluid #1, Fluid #3, and Fluid #4), the shear stresses required to remove the cuttings are significantly different. The results for both cuttings suspension and cuttings rolling have the same trend. The fluid shear stresses required for high viscosity fluids to remove the cuttings are much higher than those for low viscosity fluids. The shear stress required to remove the cuttings for Fluid #4 is 7.6 times as high as the shear stress required for Fluid #1 for cuttings suspension. Even for the fluids which are all in laminar flow regime, the fluid shear stress for Fluid #4 to transport the cuttings at the given conditions is 1.8 time as high as the Fluid #3.

The above analysis demonstrates that as the fluid viscosity increases, the fluid shear stress required to remove the same cuttings is increasing continuously. This simply means that fluid shear stress alone can not be used to evaluate hole cleaning efficiency. Therefore, Chin's conclusion is very doubtful. As the variation of the fluid viscosity widens, the shear stress required to transport the cuttings will be varied widely.

From the above analysis, it may be deduced that from the point view of consumption of energy, water is the best medium for drilled cuttings transport. Using low viscous fluid as water, the pressure drop required to remove the cuttings is much smaller than that using high viscosity fluids. Although for high viscosity fluid, a lower MTV may be required to transport the drilled cuttings up to the surface, the pressure required is much higher in order
Table 8.5.1: Actual shear stresses acting on the low-side annular wall for similar fluids when the MTV is reached

<table>
<thead>
<tr>
<th>Fluid Type</th>
<th>Shear stress (dyne/cm²)</th>
<th>MTV for rolling</th>
<th>MTV for suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid #4</td>
<td></td>
<td>280</td>
<td>287</td>
</tr>
<tr>
<td>Fluid #5</td>
<td></td>
<td>263</td>
<td>269</td>
</tr>
<tr>
<td>Fluid #6</td>
<td></td>
<td>270</td>
<td>287</td>
</tr>
</tbody>
</table>

Experimental conditions:
Annular size: 13.7 x 6.10 cm  Pipe rotary speed: 0 rpm  Cuttings density: 2.63 s.g
Cuttings size: 0.18 cm  Pipe eccentricity: 0%  Hole angle: 50 degrees

Table 8.5.2: Actual shear stresses acting on the low-side annular wall for significantly different fluids when the MTV is reached

<table>
<thead>
<tr>
<th>Fluid Type</th>
<th>Shear stress (dyne/cm²)</th>
<th>MTV for rolling</th>
<th>MTV for suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid #1</td>
<td></td>
<td>22</td>
<td>47</td>
</tr>
<tr>
<td>Fluid #3</td>
<td></td>
<td>190</td>
<td>195</td>
</tr>
<tr>
<td>Fluid #4</td>
<td></td>
<td>340</td>
<td>355</td>
</tr>
</tbody>
</table>

Experimental conditions:
Annular size: 13.7 x 6.10 cm  Pipe rotary speed: 0 rpm  Cuttings density: 2.63 s.g
Cuttings size: 0.18 cm  Pipe eccentricity: 0%  Hole angle: 50 degrees
to achieve the same hole cleaning efficiency. Theoretically speaking, rather than using low circulation rate of high viscosity fluid, low viscosity fluids at high flow rate may be more effective in removing cuttings for the whole range of hole angles from vertical to horizontal. However, for a large annulus water alone may not be practicable during drilling operations. Additional time may be required circulating for connections to clear the cuttings before making connections. If water has to be used, viscous "pills" are pumped before making connections to assist cleaning.

The above conclusion may be explained based on the laminar boundary flow. For the fluid near the annular wall, a laminar sublayer exists. This laminar sublayer will obviously reduce the exposing area of the particles to the "flowing stream" of the fluid and this will directly reduce the forces acting on the particles. As the fluid viscosity is reduced, the thickness of the laminar sublayer will be decreased and the effective stress acting on the cuttings will be increased so that the required shear stress will be reduced in order to remove the same cuttings until reaching a highly turbulent flow as the case for water. In this case the fluid shear stress required to achieve the initiation of the cuttings movement will become constant.

Based on the above discussions, the following conclusions can be derived:

• Shear stress is important for deviated hole cleaning efficiency. The higher the shear stress acting on the low-side annular, the higher the hole cleaning efficiency for the similar drilling fluids and at the same drilling conditions.

• As the fluids are significantly different from each other, shear stress can not be used for the evaluation of the drilling fluid carrying capacity. The shear stress required for the low viscous fluids to remove the cuttings out of the hole is much less than that required for high viscous fluids to clean the same cuttings.
8.5.2 Special features of the present MTV models

a. Cuttings transport mechanisms

As has been discussed previously, the two MTV models have respectively described the cuttings transport mechanism by cuttings rolling and that by cuttings suspension so that the physical concepts are very clear.

b. Direct force balance models

The present MTV models are directly derived based on the balance of forces acting on the cuttings resting on the low-side annular wall. Except for some reasonable assumptions, the models have been built based on direct force balance.

c. Classic concepts - Fluid drag force and fluid lift force

Rather than using dimensional analysis, two classic concepts are used for the establishment of the MTV models. One is the fluid drag force and the other is the fluid lift force. Fluid drag force and fluid lift force are directly used for the correlations of the MTV models; which has been proved to be a success.

d. Fluid point velocity and viscosity

In the theoretical modelling of cuttings transport and hydraulic transport, it was the fluid friction velocity \( v^* \) which is usually used for the calculations of fluid dynamic forces acting on the cuttings/particles. \( v^* \) is usually expressed as:

\[
v^* = \frac{\tau_w}{\sqrt{\rho_f}} \quad (A7.2.11)
\]

where \( \tau_w \) is the shear stress acting on the low side annular wall and \( \rho_f \) is the fluid density.

Due to the fact that \( v^* \) has the same dimension as the fluid velocity \( v_f \), it has been used to replace the fluid velocity for the calculations of the fluid dynamic forces acting on the particles(5-7). In the present study, the fluid point velocity \( v_p \) and the fluid effective
viscosity $\mu_e$ approaching the centre of the particles resting on the low-side annular wall has been directly used for the calculations of the fluid drag force and fluid lift force.

As far as the present author knows, the present author is the first author who has directly used the fluid velocity profile for the theoretical modelling of cuttings transport process.

e. **Effect of pipe rotary speed and pipe eccentricity**

Using the fluid drag force and fluid lift force, the effects of pipe rotary speed and pipe eccentricity can be directly predicted, which has never been able to be modelled by previous researchers due to the complexity of the cuttings transport process.
CHAPTER 9
ANALYSIS AND DISCUSSION OF THE FACTORS AFFECTING HOLE CLEANING EFFICIENCY

Extensive studies on drilled cuttings transport have been reported by different researchers\cite{1,36,44,45} as can be seen in chapter 2. In this chapter, a comprehensive analysis of the effects of the various drilling parameters on hole cleaning efficiency is presented based on all the literature available. The mechanisms of these effects are also discussed.

9.1 Annular fluid velocity

During rotary drilling operations drilled cuttings are removed out of the wellbore by the circulation of the drilling fluid. From the discussion presented in chapter 3, it was known that fluid velocity induces the only fluid dynamic forces to transport the cuttings up to the surface. Therefore annular fluid velocity should always be one of the most important parameters affecting hole cleaning.

In vertical wells cuttings transport ratio has been used as a measure of cuttings transport efficiency, which is expressed as\cite{7}:

$$F_T = 1.0 - \frac{v_c}{v_f}$$  \hspace{1cm} (2.1.2)

The higher the $F_T$, the higher the drilling fluid carrying capacity. Eq. 2.1.2 shows that hole cleaning efficiency in a vertical wellbore increases as the annular fluid velocity is increased. Because of the density difference between the cuttings and the drilling fluid, drilled cuttings usually have a tendency to settle towards the bottom of the wellbore. In order to remove all the cuttings out of the annulus, the fluid velocity must be high enough so that all the cuttings have a net upward transport velocity.
Hopkin(4) concluded that in order to keep a vertical hole clean, the annular fluid velocity should be 20 to 200 ft/min. above the maximum cuttings settling velocity depending on the rate of penetration. Sifferman et al(7) showed that hole cleaning efficiency increases significantly with an increase in fluid velocity. Williams and Bruce(3) recommended that 100 to 125 ft/min should be the minimum annular fluid velocity for vertical hole cleaning if turbulent flow can be maintained.

In deviated wells fluid velocity is becoming more important than that in vertical wells. If the fluid velocity is not high enough, a cuttings bed will be formed on the low side annular wall. This cuttings bed will become stationary if the fluid velocity is below a certain value. A great deal of effort has been made into the investigation of deviated hole cleaning. It has been highlighted that fluid velocity is the most important parameter affecting cuttings removal through an inclined annulus.

Iyoho(19) and Tomren et al(20) reported an extensive investigation into drilled cuttings transport through deviated wellbores. It was concluded for an example, at 10° to 30° hole angles, a cuttings bed would be formed on the low side wall of the annulus if the fluid velocity was below 2.0 ft/min. Similar results have been reported by other researchers(21,23,27-36). Thus, it is very important to maintain a high annular fluid velocity in order to avoid any hole cleaning problems.

The analysis of cuttings transport velocity profile reported in chapter 6 showed that in order to remove all the drilled cuttings out of the vertical borehole, the fluid velocity must be higher than the MTV for vertical hole cleaning. Otherwise, some cuttings will slide downward in the annulus and can not be transported up to the surface.

Similarly, the fluid velocity must be higher than the MTV for either cuttings rolling or cuttings suspension in order to transport the cuttings out of a deviated wellbore. According to the present experimental results it has been very clear that at very high fluid velocities all the cuttings can be transported up to the surface by homogeneous cuttings suspension. Reducing the fluid velocity from high to low, more cuttings will be accumulated and transported in the lower half of the annulus. Further reducing the fluid velocity, a cuttings
bed may be formed on the low side wall of the annulus. This cuttings bed may become stationary if the annular fluid velocity is further reduced. This further demonstrates the importance of annular fluid velocity on cuttings transport at various hole angles.

9.2 Hole angle

As the hole is deviated from the vertical, the axis of an inclined annulus will not be parallel with the cuttings gravity force. Thus the cuttings tend to settle towards the low side annular wall, which was shown in Fig. 3.3.2. The cuttings settling velocity may be divided into two components, one of which is vertical to the hole axis and may be expressed as:

\[ v_{sva} = v_s \cdot \sin(\Phi) \]  \hspace{1cm} (3.3.5)

Because the cuttings settling velocity \( v_s \) is greater than zero, the cuttings may sooner or later settle on the low side annular wall at the velocity of \( v_{sva} \) in an inclined wellbore. Thus cuttings settling velocity cannot be used as the measure of deviated hole cleaning efficiency.

Based on their experiments, Iyoho\(^{(19)}\) and Tomren et al\(^{(20)}\) reported that deviated hole cleaning was more difficult than vertical wells. When the hole angle is above 10\(^{\circ}\), the cuttings may travel towards the low side wall as soon as the cuttings were injected into the annulus. At 60\(^{\circ}\) and above, a cuttings bed would be formed quickly on the low side wall. 30\(^{\circ}\) to 50\(^{\circ}\) were defined as the critical hole angle because not only a cuttings bed may be formed on the low side wall, but also this cuttings bed may slide downward along the low side wall if the annular fluid velocity was not high enough.

Becker and Azar\(^{(21)}\) described the mechanisms of cuttings bed formation on the low side wall of a deviated annulus. The critical hole angle was reported to be around 45\(^{\circ}\) by Becker and Azar\(^{(21)}\), to be 40\(^{\circ}\) to 45\(^{\circ}\) by Okrajni and Azar\(^{(23)}\) who also concluded that the worst transport condition was observed at this range of hole angles as well. Martin et al\(^{(25)}\) also showed that the minimum transport velocity required for efficient hole cleaning usually reached nearly maximum at 30\(^{\circ}\) to 60\(^{\circ}\).

Brown et al\(^{(27)}\) reported that the most difficult hole angles to clean were observed to be 50\(^{\circ}\) to 60\(^{\circ}\). Sifferman and Becker\(^{(28)}\) showed that at 45\(^{\circ}\) to 60\(^{\circ}\), cuttings bed may continuously
slide downward and above 60°, the cuttings bed would not slide down even when the circulation was stopped. It was also concluded that cuttings transports at 75° and 90° are similar and the hole cleaning situations are similar for 45° and 60°. Hemphill\(^{31}\) claimed that hole cleaning was more difficult at 65° than that at 85°. However hole cleaning at the higher hole angles was much worse than that at 45°.

The present study showed that the effect of hole angle on hole cleaning is cuttings transport mechanism dependent. For cuttings rolling mechanism, the most difficult hole angles to clean occurred at 40° to 60°. The critical hole angles were also found in the above range of hole angles. However for the initiation of cuttings suspension, the most difficult hole angle was from 60° to 90° depending on the different simulated conditions.

It is clear that hole angle has not only caused a higher fluid velocity required to clean the hole, it has also made the cuttings transport process become more complicated. In vertical holes, the cuttings are either being transported up to the surface by suspension or start sliding down towards the hole bottom. However, when the hole is deviated, the cuttings are being transported in different flow patterns as described in section 5.2. This has made it more difficult to analyse the effects of the various drilling parameters on hole cleaning efficiency.

9.3 Fluid rheological properties

The importance of fluid rheological properties on drilled cuttings transport has been highlighted in section 5.5.2. Because it is such an important parameter, much effort has been spent on a better understanding of its effect on hole cleaning.

In vertical wellbores, Williams and Bruce\(^{3}\) reported that low viscosity and low gel were advantageous in removing cuttings. It was reasoned that a higher viscosity fluid would result in a lower cuttings settling velocity. However because of the fluid velocity distribution in the annulus, the cuttings may experience a greater “torque” effect in laminar flow than in turbulent flow. This made the cuttings recycling in the annulus and the actual transport velocity was lower. Zeidler\(^{6}\) found that the dependence of cuttings settling velocity on fluid viscosity decreases with an increase in particle Reynolds number. It was
concluded that low viscosity fluid in turbulent flow gave a better vertical hole cleaning than that high viscosity fluid in laminar flow regime, which was also supported by Prokop(2).

Hopkin(4) analysed the effect of fluid funnel viscosity and fluid yield value and concluded that cuttings settling velocity was reducing as long as the fluid viscosity increases. It was also shown that there was a critical value for the fluid funnel viscosity and yield point above which cuttings settling velocity will be significantly reduced. Thus it was concluded that high viscosity fluids gave a better cuttings transport. Sifferman et al(7) claimed that increasing fluid viscosity was always advantageous to vertical hole cleaning. This was consistent for both laminar flow and turbulent flow, which was supported by Tomren et al(20), Okrajni and Azar(23), Brown et al(27), Fraser(32), and Becker et al(33).

In deviated wells, Okrajni and Azar(23) concluded that fluid yield point and YP/PV ratio have little effect on cuttings transport in turbulent flow. Increasing mud yield point and YP/PV ratio would increase fluid carrying capacity at low hole angles if the fluid is in laminar flow, which is little pronounced at high hole angles. Hemphill(31) claimed that the 100 rpm readings of the Fann VG meter were the most significant value of the fluid rheological properties. At high hole angles the fluid with lower 100 rpm readings can clean the borehole better. At 45° increasing fluid yield point may reduce hole cleaning efficiency. Fraser(32) concluded that the fluid with a high viscosity at low shear rate can give a better hole cleaning.

Becker et al(32) reported that 6 rpm readings of the Fann VG meter gave the best correlation with cuttings transport. For hole angles below 45°, high viscosity fluids in laminar flow provided better cuttings transport. For hole angles above 60°, low viscosity fluids in turbulent flow were preferred. However it was concluded that if the experimental data can be extrapolated, high viscosity fluid in laminar flow may provide better hole cleaning than turbulent flow even for near horizontal wells. In laminar flow, an increase in fluid viscosity will improve cuttings transport, which was more pronounced at near horizontal angles. However in turbulent flow regime, fluid viscosity had little effect on cuttings transport.
The present study showed that two profiles need to be analysed for vertical hole cleaning. One is the fluid velocity profile and the other is the cuttings settling velocity profile across the annular space. Thus, whether increasing fluid viscosity will increase hole cleaning depends on the combination of the fluid velocity profile and cuttings settling velocity profile.

For deviated wells, the major concern is how to remove the cuttings settled on the low side annular wall. It has long been known that for an eccentric annulus, the fluid velocity is higher in the enlarged region than that the reduced region of the annulus and so is the fluid shear stress. For highly eccentric annulus, the fluid in the reduced region of the annulus may become stagnant for viscous fluids. Thus for concentric and negative eccentric annuli, both low viscosity fluid in turbulent flow and high viscosity fluid in laminar flow can give better cuttings transport. However in positive eccentric annuli, especially when the eccentricity is high, low viscosity fluid is advantageous to deviated hole cleaning. For high viscosity fluids, especially the fluid with a high yield point, the fluids in the reduced region of the annulus may become stagnant as shown in Eqs. 9.8.1 and 9.8.2. Therefore low viscosity in turbulent flow will be the best cleaning fluid.

9.4 Cuttings size and shape

9.4.1 The effect of cuttings size

For vertical wells, Piggot(1) and Sifferman et al(7) reported that small cuttings are easier to be transported than big cuttings, which was also supported by most of the following researchers. However based on their experiments, Williams and Bruce(3) concluded that the medium sized discs were more difficult to be cleaned out of the wellbore than the big sized discs, which was regarded to be caused by the cuttings shape as is discussed later.

For deviated wells, Gavignet and Sobey(24) claimed that cuttings size has strong effect on cuttings transport. The drag force acting on the small cuttings by the fluid was small and so higher flow rate was required in order to remove the cuttings bed. Sifferman and Becker(28) experimentally concluded that increasing cuttings size will increase the cuttings bed thickness formed on the low side annular wall and thus decrease fluid carrying capacity.
The present experimental investigation showed that it is not necessarily those big cuttings which are more difficult to be transported up to the surface, especially in deviated wells. When water was used as the simulated drilling fluid, bigger cuttings were more difficult to be cleaned than smaller cuttings at all hole angles. While viscous drilling fluids were used, the reverse effect may be occurred i.e. smaller cuttings may be more difficult to be cleaned. The latter is in well agreement with the conclusions by Gavignet and Sobey (24) and Williams and Bruce (3). The reason is that when water was used as the simulated drilling fluid, the cuttings could be well exposed into the fluid flow stream. Because of the less resistant force of the smaller cuttings, the smaller cuttings are easier to be transported up to the surface. As the fluid viscosity increases, the viscous layer near the low side wall of the annulus may be increased. The smaller cuttings may be just submerged within this layer. Therefore the forces acting on the smaller cuttings are lower and that acting on the big cuttings are higher so that the big cuttings may be easier to be transported.

9.4.2 The effect of cuttings shape

Pigott (1) reported that for flat particles such as shale and drilled cuttings, the required velocity for efficient hole cleaning was lower because the cuttings tend to be carried up in the position of greatest resistance to flow past it. The settling velocities for flat cuttings are only 40% of those for round cuttings. In vertical wells, the higher the cuttings settling velocity, the lower the fluid carrying capacity. Therefore, a higher hole cleaning efficiency can be obtained for flat cuttings than that for round cuttings.

Williams and Bruce (3) reported a very extensive experimental results which concluded that large cuttings may be easier to be transported than the medium sized particles. The reason is that for the medium sized particles, the thickness to diameter ratio was low (0.167), which allowed them to be turned on edge by the torque effect. Once on edge the medium sized particles may slide down so that they must be transported over the same distance for a number of times. Peden and Luo (18) investigated the effect of particle shape using the particle sphericity \( \psi \) as defined in Eq. A4.1.1. For spherical cuttings, \( \psi = 1 \). As the cuttings sphericity decreases, the fluid drag force acting on the cuttings will be increased. This will accordingly reduce the cuttings settling velocity and increase vertical hole cleaning
efficiency. Therefore it is easier to transport non-spherical cuttings than spherical ones in vertical annuli, provided the volume equivalent diameter of the cuttings remains the same.

During the present studies, the effect of cuttings shape was not investigated. Because the cuttings tend to be carried up in the position of greatest resistance to the flow past it, spherical particles should be the most difficult cuttings to be transported in vertical wells. However in highly deviated wells, because of the different cuttings transport mechanisms involved for the initiations of the cuttings movements as discussed in section 3.2.2, the effect of cuttings shape will be much more complicated than that in vertical wells. For example, at 90°, spherical cuttings may be the easiest to be removed, for these round cuttings can be removed by cuttings rolling mechanism as long as there is any force acting on the particles. However, at the same hole angle, non-spherical cuttings may be easier to be transported by the mechanism of cuttings suspension.

9.5 Fluid flow regime

The complicated fluid flow is classified into laminar and turbulent flow regimes based on the fluid flow behaviours. In the present study, the transition from laminar to turbulent has been defined according to the theoretical descriptions presented in Appendix A7.2. For power law fluids, the generalised fluid Reynolds number is defined as:

\[ N_{Re,g} = \frac{D_{eq} \cdot v_f \cdot \rho_f}{\mu_e} \]  
(A7.2.3)

and the critical Reynolds number is expressed as:

\[ N_{Re,c} = \frac{1117.3}{\eta} \]  
(A7.2.4)

If the fluid Reynolds number \( N_{Re,g} > N_{Re,c} \), the fluid is in turbulent flow regime. Otherwise the fluid is in laminar flow regime. Laminar flow has different flow characteristics with turbulent flow. The former is that the fluid is flowing in layered streamlines and the later is random, which is shown in Fig. 9.5.1.

For vertical wellbores, Pigott\(^1\) concluded that high viscosity fluid in laminar flow regime provided a better cuttings transport, which was also derived by Hopkin\(^4\), Sifferman et al\(^7\), Okrajni and Azar\(^23\), Brown et al\(^27\), Fraser\(^32\), and Becker et al\(^33\). However
a. Velocity distribution over a cross section in laminar flow regime

b.1 Velocity distribution over a cross section at an instant in time in turbulent flow regime

b.2 Time mean velocity distribution over the cross section in turbulent flow regime

Fig. 9.5.1 Flow characteristics of fluid at different flow regimes
Prokop\(^{(2)}\) reasoned that the flatter velocity profile of turbulent flow may provide a better hole cleaning than laminar flow. Therefore it was concluded that low viscosity fluid in turbulent flow can give a better hole cleaning than high viscosity fluid in laminar flow regime, which was supported by Williams and Bruce\(^{(3)}\) and Zeidler\(^{(6)}\).

For inclined wells, Tomren et al.\(^{(20)}\) concluded that turbulent flow was preferred for effective cuttings transport. However some viscosity was always desirable. The flatter turbulent velocity profile provided a better transport front for the cuttings, most of which tend to gravitate to the low side wall of the annulus. In laminar flow regime velocities near the hole wall are very small. Therefore cuttings transport may be worse in laminar flow than that in turbulent flow, depending on the level of the fluid viscosity. Kairon and Schroeter\(^{(22)}\) claimed based on their field results that turbulent flow with inner pipe rotation provided the best cuttings transport. Based on the theoretical model developed for the evaluation of deviated hole cleaning efficiency, Gavignet and Sobey\(^{(24)}\) concluded that turbulent flow gave a better deviated hole cleaning. It was suggested that keeping the fluid yield point at a relatively low value to provide a turbulent flow regime can achieve effective cuttings transport in a deviated borehole.

Okrajni and Azar\(^{(23)}\) showed that at low hole angles of 0° to 45°, laminar flow dominated hole cleaning and at high hole angles of 55° to 90°, turbulent flow provided a better cuttings transport. For the intermediate hole angles of 45° to 55°, both laminar flow and turbulent flow can give efficient cuttings transport. Becker et al.\(^{(33)}\) also claimed that laminar flow provided better cuttings transport at low hole angles (<45°) and turbulent flow gave better hole cleaning at high hole angles. However Becker et al.\(^{(33)}\) pointed out that if the experimental data can be extrapolated, higher viscosity fluid may give a better hole cleaning even at near horizontal angles.

Martin et al.\(^{(25)}\) reported that at high hole angles, turbulent flow is favourable to cuttings transport and at low hole angles high viscosity in laminar flow regime is favourable to hole cleaning, which was in well agreement with Brown et al.\(^{(27)}\) and Hemphill\(^{(31)}\). Brown et al.\(^{(27)}\) concluded that at high hole angles, water in turbulent flow provided the best cuttings transport.
The present study showed that both turbulent and laminar flow regime can achieve efficient cuttings transport at all range of hole angles in concentric, negative eccentric annuli. However in highly positive eccentric annuli where the drill pipe heavily offsets toward the low side annular wall, turbulent flow with lower viscosity will provide better hole cleaning at all hole angles.

### 9.6 Drill pipe rotary speed

For vertical annuli, Williams and Bruce\(^{(3)}\) reported that pipe rotation can improve cuttings transport. Zeidler\(^{(6)}\) reasoned that inner pipe rotation can move cuttings from the inner tube wall into the higher velocity regions in the centre of the annulus and it may also induce some turbulence to the fluid. Thus increasing pipe rotary speed can improve cuttings transport. Sifferman et al\(^{(7)}\) claimed that pipe rotary speed did not have a consistent effect on vertical hole cleaning. For viscous fluids pipe rotation gave increasing cuttings transport at higher rotary speed. For water, drill pipe rotation caused a slight decrease in cuttings transport efficiency. However generally the effect is slight. Thomas, Becker and Azar\(^{(13)}\) concluded that increasing pipe rotary speed would improve cutting transport. The effect was more pronounced at lower annular fluid velocities and appeared to be negligible at high fluid velocities. There was a threshold value of pipe rotary speed, above which further increasing pipe rotary speed has little effect on cuttings transport behaviours.

Tomren et al\(^{(20)}\) reported that pipe rotation produced only slight effect on cuttings transport performance in inclined annuli. It was reasoned that the sweeping effect of pipe rotation is minimised by the strong tendency of the cuttings to settle through the transport fluid and to form a bed on the low side annular wall. Becker and Azar\(^{(21)}\) stated that drill pipe rotation had little effect on cuttings transport at all range of hole angles. However Okrajni and Azar\(^{(23)}\) reported that pipe rotation could improve hole cleaning, especially in highly deviated wells. The reason is that pipe rotation can induce some additional turbulence in the flowing mud and it also has a mechanical, destructive influence on the cuttings bed.

Martin et al\(^{(25)}\) concluded based on their experimental results that drill string rotation is favourable to deviated hole cleaning. When the rotary speed reaches the value at which the formation of an immobile layer near the annular wall can be prevented, pipe rotation will
have significant effect on cuttings transport. If the fluid is not thixotropic, inner pipe rotation has little effect in turbulent flow and has appreciable effect at low flow rate, especially between 30° to 90° hole angles. Sifferman and Becker(28) reported that pipe rotation can reduce annular cuttings build-up under certain conditions. The effect is greatest at inclination angles near horizontal, for small cuttings (0.08 in.) and at low pipe rotary speed (50ft/min.). Hemphill(31) reported that pipe rotation only has influence on the local fluids. It has no effect on cuttings transport. However based on their field experiences, Kairon and Schroeter(22) concluded that turbulent flow with pipe rotation can provide the best deviated hole cleaning.

The present experimental study showed that the effect of pipe rotation on hole cleaning is quite annular size and fluid viscosity dependent. The effect of pipe rotation is the greatest for smaller annulus when high viscosity fluid is used as the simulated drilling fluid. In the same annulus, as the fluid viscosity decreases, the effect of fluid viscosity will be significantly reduced and the effect will be diminished when water is used as the simulated drilling fluid. As the annular size increases, the effect of pipe rotation will also be reduced. All these can be seen from the analysis presented in section 5.5.4.

Many theoretical studies have been reported concerning annular fluid flow with pipe rotation for both Newtonian and non-Newtonian fluids. The fluid in a annulus will not only flow in the direction of the annular axis, but also it will flow radially when the inner pipe is rotated. Therefore fluid flow with inner pipe rotation has been termed as fluid helical flow. The fluid helical flow behaviour has been shown in Fig. 9.6.1. When the circulating fluid is non-Newtonian fluid, it is called Non-Newtonian fluid helical flow. Based on the various studies on non-Newtonian fluid helical flow in a concentric annulus (26,43,45), the following conclusions have been drawn:

- For a Newtonian fluid, its viscosity is constant and thus not shear dependent. The axial and the tangential components of a helical flow are independent of each other.
- Pipe rotation will induce some additional shear to the fluid. Thus, the fluid viscosity will be reduced.
Fig. 9.6.1 Illustration of a helical flow system (26)
• Because of the reduced effective viscosity, the axial pressure gradient will be decreased at a constant flow rate or the flow rate will be increased at a constant axial pressure gradient.

According to Luo's(26) theoretical studies, it was known that the effect of pipe rotary speed on annular flow characteristics was mainly affected by the ratio of the inner and outer tube radii of the annulus, the flow behaviour index of the power law fluid ‘n’, and the inner pipe rotary speed. As ‘n’ increases, the effect of pipe rotary speed on the flow characteristics will be reduced. Increasing the ratio of the inner and outer radii of the annulus will increase the effect of pipe rotation. This is in well agreement with the present experimental studies. That is, for a small annulus and high viscosity fluid, the effect of pipe rotation will be most significant. However when water is used as the simulated drilling fluid, pipe rotation will have no effect on deviated hole cleaning efficiency even when a big drill pipe is used.

At different simulated drilling conditions, the effect of pipe rotation on hole cleaning may be quite different. Sometimes pipe rotation may make the cuttings there accumulate together so that a “big” cuttings will be formed. In this case it will make the hole cleaning become worse for this newly formed big cuttings may start sliding downward at a higher annular fluid velocity, which has been observed during the present experiments. This usually happens at low hole angles.

9.7 Annular size

Based on experimental data, Becker and Azar(21) claimed that a decrease in annular cross sectional area would increase cuttings concentration inside the annulus and thus decrease hole cleaning efficiency. However if the annular gap is large enough, the size of drill pipe only had a minimal effect on cuttings transport. Sifferman and Becker(28) also reported a slightly worse hole cleaning when the larger drill pipe was used. However, Gavignet and Sobey(24) showed that smaller annulus was advantageous to deviated hole cleaning. It was suggested that as large a drill pipe as possible should be used to improve deviated hole cleaning.
The present experimental investigations have showed that hole cleaning efficiency can be greatly improved by using big drill pipe i.e. smaller annulus for all hole angles. This is in well agreement with the studies by Gavignet and Sobey\(^{(24)}\). Based on the theoretical analysis of fluid flow of Herschel-Bulkley fluids, it has been known that reducing annular size will increase the fluid shear stress in the annulus at the same fluid velocity, especially that on the annular wall. This obviously will increase the force acting on the cuttings settled there. Therefore reducing annular size can improve hole cleaning efficiency at all range of hole angles from vertical to horizontal.

9.8 Drill pipe eccentricity

Nearly all wells, including "vertical" wells deviate slightly so that drill pipe does not remain centrally located in the wellbore. Because of the complex trajectory of the borehole, drill pipe may offset towards any direction in reality so that the importance of understanding cuttings transport in eccentric annuli is obvious. Thus many researchers have devoted to its investigations. The definition of drill pipe eccentricity has been defined by Iyoho\(^{(19)}\), which can be seen in Fig. 2.4.1.

For vertical wellbores, Sifferman et al\(^{(7)}\) reported a slightly better hole cleaning in an eccentric annulus than that in a concentric annulus. Thomas, Azar and Becker\(^{(13)}\) concluded that pipe eccentricity had little effect to vertical hole cleaning and the effect was oscillatory in nature. However Iyoho\(^{(19)}\) and Tomren et al\(^{(20)}\) concluded that pipe eccentricity had no effect on cuttings transport in vertical wells. It was reasoned that in vertical holes, cuttings behaviour was nearly the same for all eccentricities. The only difference was the noticeable reduction in cuttings velocity in the reduced annular area of the eccentric annulus. However because of the corresponding increase in cuttings movement in the enlarged region of the annulus, the effect appeared to cancel each other. Brown et al.\(^{(27)}\) also reported that pipe eccentricity had little effect on cuttings transport in vertical wells.

However Okrajni and Azar\(^{(23)}\) claimed based on their experiments that an eccentric annulus provided a poor cuttings transport in vertical wells. This effect was more pronounced for laminar flow than that in turbulent flow.
In a deviated wellbore Tomren et al(20) reported that a concentric annulus gave better hole cleaning than an eccentric annulus. Okrajni and Azar(23) concluded that the effect of pipe eccentricity is small when the fluid is in turbulent flow regime even at high hole angles and it became pronounced in laminar flow especially at high hole angles. In this case, an eccentric annulus provided a much worse hole cleaning.

Based on their model developed for deviated hole cleaning, Gavignet and Sobey(24) concluded that drill pipe eccentricity had a strong effect on deviated hole cleaning as the drill pipe contacts the cutting bed. However if the cuttings bed has formed and it does not contact the drill pipe, decreasing the eccentricity (and even having negative eccentricity) will have little further effect. On the other hand if the cuttings bed is touching the drill pipe, then reducing the eccentricity will have a large effect.

Brown et al.(27) reported that in deviated wells especially highly deviated wells, concentric annuli provided much better hole cleaning than that positive eccentric annuli. Sifferman and Becker(28) also claimed a worse deviated hole cleaning in a positive eccentric annulus than that in a concentric annulus.

Based on the present study, a general trend is that a better hole cleaning can be obtained when the drill pipe offsets towards the high side wall of the deviated annulus. Based on the experimental data -50% eccentric annulus provided the best hole cleaning and the worst cuttings transport was obtained for the highest 70% positive eccentric annulus. It is envisaged that the worst cuttings transport may occur when the drill pipe is lying on the low side annular wall, which has been confirmed by the study reported by Brown et al(27). It was reported that cuttings transport became much worse in 100% positive eccentric annulus than that in a concentric annulus.

From the previous studies(26, 39-42, 44) it has been known that pipe eccentricity has the following effects on the annular fluid flow:

- The local velocity in the reduced region of the eccentric annulus was lower than that in the enlarged region.
• The shear stress in the reduced region of the eccentric annulus was lower than that in the enlarged region and so is the shear rate.
• The fluid velocity varies in a wide range. The average annular fluid velocity could not represent the overall fluid flow characteristics and neither could the average fluid effective viscosity.

As we know that the only forces to transport drilled cuttings up to the surface is the fluid dynamic forces, and because pipe eccentricity has changed the fluid flow characteristics, this will surely affect cuttings transport process.

Based on the theoretical investigations into eccentric annular flow of non-Newtonian fluids, it is known that the fluid velocity and shear stress in the enlarged section of the annulus are much higher than that in the reduced region of the annulus, which have been shown in Figs. 9.8.2 and 9.8.3(40). The nomenclature is defined in Fig. 9.8.1. Based on the studies reported by Guckes(42), Haciislamoglut+U, and Peden and Luo(40), it has been known that for the fluid with a yield stress, the fluid may become stagnant in the reduced annular section while the fluid is still flowing in the rest of the annular section. Peden and Luo(40) defined the minimum pressure gradient required to start the fluid flow in an eccentric annulus. For the enlarged section of the annulus, the minimum pressure gradient required to initiate the fluid flow is expressed as:

\[
(g_p)_\text{min}^c = \frac{2.0 \cdot \tau_y}{r_2 + e - r_i}
\]  

(9.8.1)

and the minimum pressure gradient required to initiate the overall fluid flow over the entire eccentric annulus is:

\[
(g_p)_\text{min}^o = \frac{2.0 \cdot \tau_y}{r_2 - e - r_i}
\]  

(9.8.2)

From the above equations it can be seen that when the pipe offsets towards the wellbore wall, the pressure required to initiate the fluid flow is increasing. The fluid in the reduced annular section may become stagnant when the pipe eccentricity is above a certain level. In this case no cuttings in that region can be removed.
Fig. 9.8.1 Nomenclature for eccentric annuli

Fig. 9.8.2 Velocity profile in eccentric annular flow of power law fluids

Fig. 9.8.3 Shear stress profile in eccentric annular flow of power law fluids
Based on the analysis in chapter 3, it was seen that when the drill pipe offsets towards the low side annular wall, the fluid velocity there will be reduced and so will the fluid forces acting on the cuttings. This obviously will reduce deviated hole cleaning efficiency. Therefore positive eccentric annulus is disadvantageous to deviated hole cleaning. When the drill pipe offsets towards the higher side annular wall, the fluid velocity close to the low side annular wall will be increased. Thus it is advantageous to cuttings transport. The present experimental results are in good agreement with the above theoretical analysis. Chin(29) also claimed that the bottom averaged viscous shear stress is largely responsible for hole cleaning and cuttings bed removal.

It was observed during the present experiments that when low viscosity fluid was used, the fluid velocities in the different regions of an eccentric annulus do not vary much. However as the high viscosity fluid was used, the fluid velocity in the enlarged region of the annulus was much higher than that in the reduced region of the annulus. Therefore in a highly positive eccentric annulus, low viscosity fluid is preferred. Because of the flow characteristics of low viscosity fluid in turbulent flow, it will provide a "uniform" velocity profile even in a highly eccentric annulus. Accordingly it will provide a better deviated hole cleaning. In a vertical annulus, if the average cuttings transport ratio is used as the measure of hole cleaning efficiency, pipe eccentricity may have little effect on the hole cleaning. In this case, the reduction of the cuttings moving velocity in the reduced region of the annulus will be compensated by the increased cutting moving velocity in the enlarged region of the annulus. However if the MTV is used as the measure of hole cleaning efficiency, eccentric annuli will have worse hole cleaning than concentric annuli. The reason is that the cuttings in the reduced region of the annulus may start sliding downward at a relatively higher fluid velocity because of the reduced fluid velocity there.

9.9 Density of the drilling fluid

In vertical annuli Hopkin(4) claimed based on his theoretical calculations that increasing the fluid density can improve cuttings transport. Increasing the fluid density to approximately 15 ppg should reduce the cuttings settling velocity to 50% of the cuttings settling velocity in water. Sifferman et al(7) reported that an increase in fluid density will increase cuttings
transport. Sifferman and Becker(28) and Martin et al.(25) concluded that cuttings beds were substantially reduced by a small increase in mud weight in deviated wells. Based on the theoretical analysis, it is known that increasing the fluid density will decrease the effective gravitational force of the cuttings, which is the only force to resist the cuttings movement. Therefore hole cleaning should be improved by an increase in fluid density, which was also supported by the present experiments.

9.10 Type of drilling fluid

Sifferman and Becker(28) and Hemphill(31,86) all reported that fluid type had little effect on cuttings transport as long as their rheological properties are the same. Based on both the theoretical analysis and the present experimental data, fluid type has no effect on drilled cuttings transport at all hole angles.

9.11 Cuttings concentration/rate of penetration

In vertical annuli Sifferman et al.(7) concluded that cuttings concentration had no consistent effect on the cuttings transport ratio. Certainly the effect was minor in the range of 0 to 6% by volume cuttings concentration, which covered the usual drilling conditions. However based on the conclusions by Hopkin(4), the rate of penetration had very important effect on the minimum transport velocity required for vertical hole cleaning. It was suggested that the fluid velocity required for fast upper hole drilling was much higher than that required for slow and hard rock drilling operations.

For vertical wells, Pigott(1) suggested that in order to avoid hole trouble, the cuttings concentration in the annulus should be less than 5% by volume, which was confirmed by Hopkin(4) based on his field experiences as has been shown in Table 9.11.1. But Iyoho(19) concluded that a limit of 5% by volume was too conservative, especially in inclined annuli. If the conclusion by Pigott and Hopkin is true, the cuttings concentration i.e. the rate of penetration will have appreciable effect on hole cleaning, for the cuttings concentration in vertical annuli can be correlated against the rate of penetration by(26):
\[ C_s = \frac{d_2^2 \cdot v_d}{F \cdot \left( d_2^2 - d_1^2 \right) \cdot v_f} \]  

Eq. 9.11.1 shows that the cuttings concentration is linearly proportional to the rate of penetration. Therefore increasing rate of penetration will greatly increase the cuttings concentration in the drilling annulus.

**Table 9.11.1 Effect of cuttings concentration on hole conditions**(4)

<table>
<thead>
<tr>
<th>Well No. (in.)</th>
<th>( d_2 ) (in.)</th>
<th>( d_1 ) (in.)</th>
<th>( v_d ) (ft/hr)</th>
<th>( v_f ) (ft/min)</th>
<th>( v_t ) (ft/min)</th>
<th>( C_s )</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>4.62</td>
<td>Occasional mud rings</td>
</tr>
<tr>
<td>B</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.98</td>
<td>No hole trouble</td>
</tr>
<tr>
<td>C</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.30</td>
<td>No hole trouble</td>
</tr>
<tr>
<td>D</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.70</td>
<td>No hole trouble</td>
</tr>
<tr>
<td>E</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.10</td>
<td>No hole trouble</td>
</tr>
<tr>
<td>F</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.90</td>
<td>No hole trouble</td>
</tr>
<tr>
<td>G</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.56</td>
<td>Stuck pipe</td>
</tr>
<tr>
<td>H</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.15</td>
<td>Trip for mud rings</td>
</tr>
<tr>
<td>I</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.90</td>
<td>Stuck pipe</td>
</tr>
<tr>
<td>J</td>
<td>7-7/8</td>
<td>4.5</td>
<td>450</td>
<td>350</td>
<td>240</td>
<td>3.94</td>
<td>Trip for mud rings</td>
</tr>
</tbody>
</table>

For deviated wells, Tomren et al(20) reported that an increase in cuttings concentration will reduce the transport performance of the drilling fluids. Gavignet and Sobey(24) stated that penetration rate has little effect on deviated hole cleaning for hole angles above 60°. Rate of penetration normally makes little difference as far as bed thickness is concerned. Sifferman and Becker(28) concluded that increasing cuttings concentration will reduce hole cleaning efficiency, which was also concluded by the present author.
CHAPTER 10
THE MTV COMPUTER PACKAGE FOR HOLE CLEANING
DESIGN AND ANALYSIS

A new computer package for hole cleaning design and analysis has been developed by the present author together with the drilled cuttings transport research group at Heriot-Watt University. The package is designed as a useful tool for the field engineer to predict the MTV required for efficient hole cleaning during drilling operations, details of which are presented in the present chapter. It can also be seen in a recent publication^{84}.

10.1 Introduction

An extensive investigation into annular flow of non-Newtonian fluids and drilled cuttings transport at various hole angles has been presented in the preceding chapters, which includes both theoretical modelling and experimental studies:

- Annular flow of Herschel-Bulkley non-Newtonian fluids through concentric annuli;
- An extensive experimental investigation of drilled cuttings transport at various hole angles;
- A new model for cuttings settling velocity in dynamic non-Newtonian drilling fluids and the predictions of the MTV for vertical hole cleaning;
- The predictions of cuttings settling velocity profile and cuttings transport velocity profile across the annulus between the drill pipe and the borehole wall;
- The MTV models for the predictions of deviated hole cleaning.

For the maximum benefits of the sponsors for the project Drilled Cuttings Transport in Deviated Wells, who have been acknowledged in the acknowledgement, a MTV computer package for hole cleaning design and analysis has been developed by the present author.
together with the cuttings transport research group at Heriot-Watt University. As a matter of fact, the MTV package has been one of the major final deliveries to the sponsors of the project. It needs to be highlighted that except for the incorporation of the above theoretical studies, the following work has also been incorporated into the MTV package:

- Analysis of the rheological properties of actual drilling fluids using different fluid rheological models, including Bingham plastic model, power law model and Herschel-Bulkley model;
- Fluid flow of Herschel-Bulkley non-Newtonian fluids through concentric annuli with pipe rotation\(^{(87)}\);
- Fluid flow of Herschel-Bulkley non-Newtonian fluids through eccentric annuli with/without pipe rotation\(^{(87)}\);
- Predictions of the thickness of the stationary cuttings bed if there is;
- The critical velocity for the transition from laminar to turbulent flow regime\(^{(56)}\);
- Analysis of cuttings radial positions on the MTV for hole cleaning;
- Bed erosion analysis once a stationary cuttings bed is formed\(^{(88)}\);
- Effect of pipe orbital motion on the MTV for efficient cuttings transport\(^{(88)}\).

All the detailed theoretical background and the concepts of the above studies are presented when necessary. The MTV package is developed using the XVT Windowing toolkit which lets the MTV program conform to the native GUI of the hardware platform on which the MTV software is run. Thus, the program looks like a Microsoft Windows program when running on a PC, like a Mac program when running on a Macintosh, and like Motif when running under Motif on any UNIX machine.

The software package currently operates in a Microsoft Windows system environment on PCs. The source codes of the package is programmed in FORTRAN and the interfaces are programmed in Microsoft C/C++. To run the package, the dynamic libraries from the XVT Toolkit are required.
10.2 Functions of the MTV package

The designing philosophy of the MTV package is to provide a useful tool for the field engineer to predict and analyse hole cleaning situations during actual drilling operations. Therefore, it has been designed to implement different tasks covering all the related areas concerning hole cleaning, including fluid rheological properties, annular flow of non-Newtonian fluids and the MTV for efficient cuttings transport at various hole angles. As a summary, the MTV package has been designed and built in modules to allow the user to:

- Define, from the viscometer readings, the appropriate rheological model for a specified drilling fluid, including power-law model, Bingham plastic model, or Herschel-Bulkley model.
- Model, for a specified drilling fluid and annular geometry, the annular flow profiles, including the velocity profile, shear rate/shear stress profile and fluid viscosity profile.
- Predict the minimum circulation rates required for efficient cuttings transport at a given operational condition of hole angle, pipe rotation and eccentricity as well as fluid properties, including the MTV for both cuttings suspension and cuttings rolling.
- Simulate the effects of the various drilling parameters on hole cleaning efficiency. The user can assess the sensitivity of the MTV to changes in individual parameters.
- Compute the thickness of a stationary cuttings bed if the actual fluid velocity is below the MTV for cuttings rolling.
- Predict the cuttings settling velocity profile and cuttings transport velocity profile across the entire annular space.
- Do the sensitivity analysis of the cuttings radial position on the MTV for efficient cuttings transport.
- Analyse the cuttings bed erosion when a stationary cuttings bed has been formed.
10.3 System architecture

The MTV package is composed of different modules to carry out the calculations required for each of the functions illustrated in section 10.2. It also includes various user menus to facilitate the required data input and the output of the processed results from the package. The menus are also used to choose the different modules or different facilities so that the preferred data input, data processing or the output of the processed results can be accomplished. The overall system architecture has been shown in Fig. 10.3.1.

10.3.1 Modules of the MTV package

The MTV package is made up of seven distinct but interrelated modules, each of which will make special computations or data processing. The seven modules include:

10.3.1.1 'Rheogram' module

This module is used for the definition of the most appropriate rheological model for the drilling fluid in use. The best model representing the fluid rheological properties is selected on the basis of curve-fitting of the viscometer readings. In this module, three different fluid rheological models have been considered:

- Power law model as expressed in Eq. 3.4.2b;
- Bingham plastic model as expressed in Eq. 3.4.5b;
- Herschel-Bulkley model as expressed in Eq. 3.4.7b.

For this module, maximum six and minimum two non-zero viscometer readings are required for the evaluation of the fluid rheological parameters. The module calculates the fluid rheological parameters of the different models by regression analysis. Then the comparison between the actual viscometer readings and the model predictions is made for the relationship of:

- Shear rate versus shear stress;
- Shear rate versus fluid effective viscosity.
Fig. 10.3.1 System architecture of the MTV Package
This module has also been designed in such a way that by using two viscometer readings respectively at the shear rates of 3/6 rpm, 100/200 rpm, and 300/600 rpm for Fann VG viscometer, the various rheological parameters of the three different models can be evaluated. For other viscometers, the corresponding readings as those for Fann VG viscometer are used for the calculations. The results can be output in tabular form for direct analysis.

10.3.1.2 'Annular Flow Profiles' module

This module computes the fluid velocity profile and the corresponding shear rate/stress and fluid viscosity profiles for the given drilling fluid in a specified annular geometry. It can also calculate the pressure gradient for a given flow rate. It needs to be highlighted that except for the annular flow of power law fluids in turbulent flow regime, all the annular flow modelling in the MTV package is for the generalised non-Newtonian fluids - Herschel-Bulkley model. The various modellings are briefed as follows:

a. Laminar flow through concentric annuli without pipe rotation

A momentum balance approach was used to derive the various flow equations for the fluid velocity profile, shear rate/stress profile, and fluid viscosity profile. A solution procedure was developed to solve the various flow equations for Herschel-Bulkley fluids, which can be seen in chapter 6.

b. Laminar flow through concentric annuli with pipe rotation

The same approach as above was adopted to generate the governing equations for the system. However, the boundary conditions were altered to account for pipe rotation. The governing equations were then integrated using the Simpsons Rule and the Secant method.

c. Laminar flow through eccentric annuli with pipe rotation

The same approach as above was adopted to generate the governing equations for the system with the eccentric annulus represented by an infinite set of concentric annuli. The equation of motion is also integrated using Simpson’s Rule and the Secant method.
The annular space is described using the Bipolar Co-ordinate system, as defined by Guckes (14). The equation of motion and the equation of continuity are also described in Bi-polar co-ordinates. The equation of motion is then discretized using a finite difference approximation and the resultant sparse matrix is solved by the Simultaneous Over-Relaxation (SOR) method. The Simpson's Rule is used for the numerical integration of the flow rate equation, and the Secant method is used for the iterative solution of the flow rate.

This subroutine is to calculate the annular flow profiles of power law fluids through concentric annuli without pipe rotation. So far, this is the only subroutine available in the MTV package for the calculations of turbulent fluid flow of non-Newtonian fluids.

10.3.1.3 'MTV - Single Section' Module

This module, which is the most important module in the MTV package, predicts the MTV for a given drilling condition. It also allows the user to carry out sensitivity analysis of cuttings transport efficiency with respect to the various drilling parameters. The effect of drill pipe orbital motion on the MTV has also been incorporated into the package. As a summary, the 'MTV - Single Section' module can predict:

- The MTV for cuttings suspension;
- The MTV for cuttings rolling;
- Thickness of the stationary cuttings bed if there is;
- The critical velocity for the transition from laminar to turbulent flow regime;
- Sensitivity analysis of a wide range of drilling parameters on hole cleaning.

In the previous discussions, it has been known how to predict the MTV using the MTV models. The critical velocity for the transition from laminar into turbulent flow regime is calculated by Eq. A7.2.5. How to vary a drilling parameter to simulate its effect on the
MTV is also very clear to understand. However, the effect of drill pipe orbital motion on the MTV and the prediction of the stationary cuttings bed need to be further discussed.

a. Effect of drill pipe orbital motion on the MTV\textsuperscript{(88)}

The effect of drill pipe orbital motion is briefly discussed in section 5.5.9. It has been demonstrated that drill pipe orbital motion has little effect on the MTV for cuttings suspension, but it has significant effect on the MTV for cuttings rolling depending on the drilling parameters. Based on the experimental data, the effect of drill pipe orbital motion on the MTV has been found to be a function of:

- Fluid effective viscosity;
- Orbital rate;
- Hole angle.

To theoretically model the effect of orbital motion on the MTV is extremely complicated, it is beyond the scope of the present study. Its effect on the MTV has been correlated on the basis of simple statistical analysis. The correlations obtained have been shown in Table 10.3.1.

b. Prediction of the stationary cuttings bed\textsuperscript{(85)}

When the fluid velocity is below the MTV for cuttings rolling, a stationary cuttings bed will be formed on the low-side annular wall. It is interesting to know the size of the cuttings bed if there is. Therefore, an attempt is made to predict the thickness of the stationary cuttings bed. In doing so, some similar assumptions as those by Larsen et al\textsuperscript{(85)} are made:

- For a stable cuttings bed, the fluid velocity above the bed should be equal to the MTV for cuttings rolling;
- Once formed, the stationary cuttings bed will have a flat surface so that the thickness of this bed will be constant;
- Drill pipe eccentricity is the same for the sections considered.
Table 10.3.1 Correlations for the effect of drillpipe orbital motion on the MTV

<table>
<thead>
<tr>
<th>Orbital Speed</th>
<th>0 - 40 degrees</th>
<th>40 - 60 degrees</th>
<th>60 - 90 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>rpm</td>
<td>AP&gt;80 cp</td>
<td>AP&lt;=80 cp</td>
<td>AP&gt;80 cp</td>
</tr>
<tr>
<td>60 - 80</td>
<td>0.5 x MTV(0)</td>
<td>0.7 x MTV(0)</td>
<td>0.69 x MTV(0)</td>
</tr>
<tr>
<td>80 - 150</td>
<td>0.40 x MTV(0)</td>
<td>0.42 x MTV(0)</td>
<td>0.48 x MTV(0)</td>
</tr>
</tbody>
</table>

Note:
1. MTV(0) is the predicted MTV for cuttings rolling at concentric annuli without pipe rotation.
2. AP is the fluid effective viscosity at the shear rate of 170 l/s.
With these assumptions, the cuttings bed thickness can be predicted using the procedure as follows:

- Calculate the MTV for cuttings rolling using the MTV models developed and convert it into the minimum flow rate $Q_{mtv\text{-}roll}$:

- Calculate the total annular area of the annulus $A_a$ by Eq. 10.3.1:
  \[
  A_a = \frac{\pi}{4} \left( d_2^2 - d_1^2 \right) 
  \]  
  \[ (10.3.1) \]

- Calculate the area occupied by the stationary cuttings bed using Eq. 10.3.2:
  \[
  A_{bed} = A_a \left( 1.0 - \frac{Q_{pump}}{Q_{mtv\text{-}roll}} \right) 
  \]  
  \[ (10.3.2) \]

- Convert the annular area occupied by the cuttings bed $A_{bed}$ into bed height which is measured starting from the low-side annular wall vertical to the hole axis.

It can be seen from Eq. 10.3.2 that if the actual pump rate $Q_{pump}$ is greater than the flow rate required for cuttings rolling $Q_{mtv\text{-}roll}$, a negative area $A_{bed}$ will be obtained. In this case, the actual stationary bed height should be zero i.e. no cuttings bed exists in the annulus. Otherwise, a stationary cuttings bed will exist, which is then calculated.

10.3.1.4 'MTV - Multiple Sections' Module

Because of the different geometry and hole angles at different depths of the wellbore, hole cleaning will be different from section to section. This module allows the user to choose up to four potential problem zones along the wellbore to do simultaneous hole cleaning efficiency analysis so that remedies can be taken to improve the hole cleaning based on the worst hole cleaning section. Similar to the MTV module, the calculations for the four different sections of the wellbore include:

- The MTV for cuttings suspension;
- The MTV for cuttings rolling;
- Thickness of the stationary cuttings bed if there is;
- The critical velocity for the transition from laminar to turbulent flow regime.
10.3.1.5 'Relative Velocity of Cuttings' Module

Cuttings settling velocity and transport velocity are very important factors to be considered for hole cleaning analysis. This module predicts the cuttings settling velocity profile and cuttings transport velocity profile across the entire annular space in a given drilling condition. The procedure for the calculations of the cuttings relative velocity profiles is as follows:

- Calculate the annular flow profiles for the given drilling fluid, annular geometry and fluid flow rate, including the fluid velocity profile and shear rate profile;
- Predict the cuttings settling velocity profile using the cuttings settling velocity models derived in chapter 7;
- Determine the cuttings transport velocity profile by subtracting the fluid settling velocity profile from the fluid velocity profile.

It needs to be pointed out that the cuttings relative velocity profiles are valid for vertical wellbores and can only be taken as a reference for deviated boreholes.

10.3.1.6 'Radial Cross-section Analysis of MTV' Module

From the definitions of the MTV, it has been seen that the criteria for the MTV predictions are:

- The cuttings touching the low-side annular wall are to be considered, where the cuttings are most difficult to be transported due to the combination of low local fluid viscosity and low local fluid velocity experienced by the cuttings;
- As long as the MTV is achieved, all the cuttings can be removed out of the borehole i.e. complete hole cleaning can be obtained.

However, in actual practices, the MTV may not be achievable due to the limitations of drilling facilities or other factors. In this case, this module can be used to do a sensitivity analysis of the cuttings radial positions on the MTV as discussed in section 7.6.4 for the MTV for vertical hole cleaning. This is basically to analyse:
• How the MTV varies with the changes of cuttings radial positions;
• How much of the annulus can be cleaned, especially for vertical holes.

In this case, rather than simply considering the cuttings on the low-side annular wall, the cuttings at different radial positions are being analysed. Corresponding to each radial position of the cuttings, the MTV for both cuttings suspension and cuttings rolling can be calculated so that the MTV versus the cuttings radial positions can be obtained. For vertical boreholes, it can be visualised how much of the annulus can be cleaned. It needs to be pointed out that the cuttings radial position analysis is only valid for vertical wells. It can only be taken as a reference for deviated wells.

10.3.1.7 'Bed Erosion Analysis' Module

When a stationary cuttings bed is formed on the low-side annular wall, how to clear this bed so that the drilling operation can proceed smoothly is very crucial. This module will make the necessary calculations to show the user how to modify the drilling fluid to clear this stationary cuttings bed.

Some special experiments for cuttings bed erosion has been carried out by the cuttings transport research group at Heriot-Watt University. It is observed that as long as a stationary cuttings bed is formed on the low-side annular wall, it is very difficult to clear it, especially when highly viscous fluids are used. Based on the experimental data, it is far easier to clear the bed using low viscous fluid in turbulent flow regime than that high viscosity fluid in laminar flow regime. When highly viscous fluids are used, the fluid velocity must exceed the MTV for cuttings suspension in order to clear the cuttings bed effectively. This module makes the following calculations:

• The MTV for cuttings suspension;
• The MTV for cuttings rolling;
• The actual fluid velocity based on the pump rate;
• The critical fluid velocity for the transition from laminar to turbulent flow regime.
If the actual fluid velocity is higher than the MTV for cuttings rolling and the fluid is in turbulent flow regime, the bed can be effectively cleared. If the MTV for cuttings suspension is achieved and the fluid is in laminar flow regime, the bed can also be cleared. Otherwise, some recommendation will be given on how to improve the drilling fluid to erode the stationary cuttings bed out of the borehole.

10.3.2 Description of the main user menus

The MTV package is made up of five main user menus, which are discussed as follows:

10.3.2.1 'FILE'

This menu contains the file management facilities namely:

- New
- Open
- Save
- Save as
- Units
- Quit
- System

This part of the package allows the user to get access to the saved input data files by "Open" so that the same drilling parameters are not required to be input again. Much time is saved! "New" means that you start a calculation by using a new set of drilling parameters. For the convenient of the field engineers, two unit systems have been defined in the package including Field Unit System and C.G.S Unit System for the user to choose from. "Save" and "Save as" are used to save the current files either by the same name or by a newly defined name. "quit" is to quit the MTV package. "System" is to show the title page of the MTV package, which tells you the main functions of the package and the producer details of the package.
10.3.2.2 ‘INPUT’

This menu is designed in such a way that the user need only to input the data required for the chosen module. There is a great deal of data which is common to all modules. Therefore, once a piece of data has been input for a particular module it is stored and displayed upon selection of subsequent modules. The "INPUT" menu has the following options:

(i) The Rheogram option is used for the determination of the most appropriate rheological model to describe the drilling fluid properties on the basis of the viscometer readings using curve-fitting technique. The input data required for this option are the type of viscometer used and the actual viscometer readings. A minimum of two and a maximum of six viscometer readings are required. You may also input the measured yield point. At present, the package allows three types of viscometer measurements, including:

- Fann VG viscometer
- HAAKE viscometer
- Preferred viscometer

For the preferred viscometer, except for the viscometer readings, the user also needs to define the following parameters:

- The rotary speeds of the chosen viscometer;
- The conversion factor from rotary speed rpm into shear rate 1/s;
- The conversion factor from viscometer readings into shear stress dyne/cm².

(ii) The Annular Flow Profiles option is used to input the drilling parameters required to calculate the fluid annular flow profiles. These include:

- Fluid rheological properties;
- Fluid flow rate, density and the measured yield point;
- Annular geometry;
- Drill pipe eccentricity;
For the input of fluid rheological properties, there are two options for the user to choose from. One is the viscometer readings, which the input data will be exactly the same as those for the Rheogram option. However, once the user have chosen the fluid model, then one needs to define the type of the rheological model (power law, Bingham plastic or Herschel-Bulkley). Thereafter, the rheological parameters for the chosen model need to be input.

(iii) The MTV - Single Section option is used to input the drilling parameters required to calculate the MTV for a single section of the wellbore, including both the MTV for cuttings rolling and the MTV for cuttings suspension. The input data required are:

- Fluid rheological properties;
- Fluid flow rate, fluid density and measured fluid yield point;
- Annular geometry;
- Drill pipe eccentricity;
- Drill pipe rotary speed;
- Hole angle;
- Cuttings size and density;
- Rate of penetration.

The input of fluid rheological properties are exactly the same as those for the Annular Flow Profiles option.

(iv) The MTV - Multiple Sections option is used to input the drilling parameters required to calculate the MTV for up to four different sections along the borehole, including both the MTV for cuttings rolling and the MTV for cuttings suspension. The input data required for this option include:

- Fluid rheological properties;
- Fluid flow rate, fluid density and measured yield point;
- Drill pipe eccentricity;
- Drill pipe rotary speed;
• Cuttings size and density;
• Rate of penetration;
• Hole angles for up to four different sections of the borehole;
• Annular geometry for up to four different sections of the wellbore.

The input of fluid rheological properties are exactly the same as those for the **Annular Flow Profiles** option.

(v) The **Relative Velocity of Cuttings** option is used to input the drilling parameters required to calculate the cuttings settling velocity profile and cuttings transport velocity profile. The input data are exactly the same as those for the **MTV - Single Section** option.

(vi) The **Radial Cross-section Analysis of MTV** option is used to input the drilling parameters required to calculate the MTV at various cuttings radial positions in the annulus. The input data are exactly the same as those for the **MTV - Single Section** option.

(iii) The **Bed Erosion Analysis** option is used to input the drilling parameters required to analyse cuttings bed erosion once a stationary cuttings bed is formed on the low-side annular wall. The input data are exactly the same as those for the **MTV - Single Section** option.

10.3.2.3 ‘RESULTS’

This menu allows the selection of the specific output of the processed results in tabular form. The Windows system also allows the access to the input data whilst viewing the processed results.

(i) The **Rheogram** option presents analysis results for the fluid rheological properties, which include:

- Fluid rheological parameters of the three different models. The results are either based on all the six viscometer readings by regression analysis or based on two
viscometer readings respectively at the shear rates of 3/6 rpm, 100/200 rpm, or 300/600 rpm for Fann VG viscometer or at the corresponding shear rates for other viscometers. If regression analysis is used, the corresponding regression coefficients for each of the three models are also presented.

- Shear rate versus shear stress. The results based on both the viscometer readings and model predictions are shown side by side for direct comparison.
- Shear rate versus effective viscosity. The results based on both the viscometer readings and model predictions are shown side by side for direct comparison.

(ii) The **Annular Flow Profiles** option presents the annular flow profiles across the entire annular space, including:

- Fluid velocity versus the radial position;
- Fluid shear stress versus the radial position;
- Fluid shear rate versus the radial position;
- Fluid effective viscosity versus the radial position.

For eccentric annuli, the profiles both at the maximum clearance section and at the minimum clearance are to be shown.

(iii) The **MTV - Single Section** menu allows access to processed results for the MTV calculations. These include:

i. MTV at a specified drilling operation;

ii. MTV as a function of:
   - Hole Angle
   - Wellbore Diameter
   - Drill pipe Diameter
   - Cuttings Diameter
   - Fluid non-Newtonian index (n)
   - Fluid Consistency index (K)
   - Fluid Yield Point (YP)
- Fluid Plastic Viscosity (PV)
- Fluid Density
- Rate of Penetration (ROP)
- Pipe Eccentricity
- Axial Pipe Rotary Speed
- Effect of Orbital motion

(iv) The **MTV - Multiple Sections** menu is to do a simultaneous analyse of the hole cleaning efficiency for up to four specified sections along the borehole. Then, the results are output together in one table.

(v) The **Relative Velocity of Cuttings** menu is to calculate the cuttings settling velocity profile and cuttings transport velocity profile across the entire annular space. The output are:

- Cuttings settling velocity versus cuttings' radial position;
- Cuttings transport velocity versus cuttings' radial position.

As the case for the annular flow profiles, the relative velocity profiles are shown for both the maximum annular clearance section and the minimum annular clearance section for an eccentric annulus.

(vi) The **Radial Cross-section Analysis of MTV** menu is to analyse the effect of cuttings radial positions on the MTV. The output includes:

- Radial position versus MTV for both cuttings rolling and cuttings suspension

(vii) The **Bed Erosion Analysis** menu is to make the necessary calculations on how to effectively clear the stationary cuttings bed once formed on the low-side annular wall. Then further recommendations will be presented as an output.

10.3.2.4 ‘PLOTS’

This menu allows a graphical display of the processed results. The plots correspond to each of the modules defined.
This menu can print both the data files and the plots shown on the computer screen so that hard copies for the data input or processed results can be obtained both in tabular form and in graphic form.

10.4 Application of the MTV package

A comprehensive computer package for hole cleaning analysis and design has been presented in the previous sections. In this section, the major applications of the computer package are highlighted. As a summary, the applications of the MTV package include:

- Definition of drilling fluid rheology;
- Definition of annular flow profiles of non-Newtonian drilling fluids;
- Hole cleaning efficiency analysis.

As a field tool, the MTV package can be used for sensitivity analysis of the effects of the various drilling parameters on hole cleaning efficiency. In field practice, whenever there is any hole cleaning problem, the package can be used to identify the impact of a change of any specific parameter so that the specified parameter can be modified for a better cuttings transport.

Specific case studies are now used to illustrate how the MTV package can be effectively used for the analysis of hole cleaning efficiency including the interpretations of the effects of fluid rheology and annular flow profiles of actual drilling fluids.

10.4.1 General comments

In order to effectively clean the hole, especially a deviated wellbore, the MTV must be achieved. Generally the MTV for cuttings rolling is less than the MTV for cuttings suspension as illustrated in Fig. 10.4.1. When designing for optimum hydraulics, the minimum allowable annular velocity should at least be equal to the MTV for cuttings rolling. Operating below the MTV for cuttings rolling will result in a cuttings bed being formed, which may cause serious hole cleaning problems.
10.4.2 Effect of fluid rheology

The impact of fluid rheology on hole cleaning has been simulated in a typical drilling environment. The annular geometry and cuttings properties for the example well are shown in Table 10.4.1. The Fann VG viscometer readings of the two different drilling fluids, Fluid A and Fluid B, are shown in Table 10.4.2, whose rheograms are also plotted in Fig. 10.4.2.

Table 10.4.3 shows the MTV for both cuttings rolling and cuttings suspension when using Fluid A and Fluid B respectively as the drilling fluid. For the same annular geometry and other drilling parameters, the MTV both for cuttings rolling and for cuttings suspension are much lower for Fluid B than for Fluid A. The difference is due solely to the drilling fluid properties.

From Table 10.4.2 and Fig. 10.4.2, it can be seen that the major difference of the two fluids is the low shear rate viscometer readings. At 600 rpm, Fluid A and Fluid B have nearly the same viscometer reading. However, at low shear rates, the viscometer readings are much higher for Fluid B than for Fluid A. This demonstrates the importance of the fluid rheogram on the effect of hole cleaning efficiency, which appears to be in agreement with field experiences. That is, fluids with high viscometer readings at low shear rates can provide a better cuttings transport, especially in highly deviated wells.

In fact, the above results can be also explained based on the fluid velocity profile. Analysis of the fluid velocity profiles generated by each of the two different fluids in a concentric annulus, which is presented in Fig. 10.4.3, shows that Fluid B has a higher sweeping efficiency of the annular clearance than that of Fluid A because of the higher fluid velocity close to the borehole wall. Therefore, fluid velocity profile is a good reflection of the cuttings transport efficiency. A flatter velocity profile can provide a more efficient cuttings transport.
Fig. 10.4.1 Comparison of MTV for cuttings rolling and cuttings suspension

Fig. 10.4.2 Comparison of the rheograms of Fluid A and Fluid B

Fig. 10.4.3 Comparison of the fluid velocity profiles for Fluid A and Fluid B
Table 10.4.1 Drilling parameters for the effect of fluid rheology on the MTV

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Angle</td>
<td>58</td>
</tr>
<tr>
<td>Hole Size (in)</td>
<td>12.25</td>
</tr>
<tr>
<td>Pipe diameter(in)</td>
<td>6.625</td>
</tr>
<tr>
<td>Rotary speed (rpm)</td>
<td>0</td>
</tr>
<tr>
<td>Eccentricity (%)</td>
<td>0</td>
</tr>
<tr>
<td>Cuttings size(cm)</td>
<td>0.17</td>
</tr>
<tr>
<td>Cuttings density (s.g)</td>
<td>2.600</td>
</tr>
<tr>
<td>ROP (ft/hr.)</td>
<td>206</td>
</tr>
</tbody>
</table>

Table 10.4.2 Drilling fluid properties of Fluid A and Fluid B

<table>
<thead>
<tr>
<th>Viscometer Readings at rpm</th>
<th>Fluid A</th>
<th>Fluid B</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>96</td>
<td>94</td>
</tr>
<tr>
<td>300</td>
<td>58</td>
<td>78</td>
</tr>
<tr>
<td>200</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>100</td>
<td>29</td>
<td>58</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>40</td>
</tr>
</tbody>
</table>

Fluid density 9.5 ppg 9.5 ppg

Table 10.4.3 MTV for Fluid A and Fluid B

<table>
<thead>
<tr>
<th>Fluid No.</th>
<th>MTV (ft/min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rolling</td>
</tr>
<tr>
<td>Fluid A</td>
<td>279</td>
</tr>
<tr>
<td>Fluid B</td>
<td>29</td>
</tr>
</tbody>
</table>
10.4.3 Effect of hole angle

The modelling of the MTV has clearly demonstrated that hole angle has a major impact on hole cleaning efficiency.

Fig. 10.4.1 demonstrates the general trend for the effect of hole angle on the MTV for the given fluid properties. It can be observed that the effect of hole angle is different for the two different cuttings transport mechanisms. For cuttings rolling, the MTV increases as the hole angle increases from the vertical until reaching about 55°. Thereafter, a further increase in hole angle results in a reduction of the MTV. However, for cuttings suspension, the MTV increases rapidly up to approximately 60° but increases more slowly for higher hole angles.

In well planning therefore, the MTV package can be used to optimise the well trajectory from the standpoint of hole cleaning.

10.4.4 Effect of rate of penetration

Fig. 10.4.4 shows the effect of rate of penetration on the MTV based on Fluid A. As can be observed, an increase in the rate of penetration will reduce hole cleaning efficiency. This illustrates that there is the need for a rational compromise between high rate of penetration and good hole cleaning. In actual practices, the rate of penetration needs to be controlled in order to avoid the build up of drilled cuttings in the annulus.

10.4.5 Effect of pipe eccentricity

The present experiments have demonstrated that a higher MTV is required to transport cuttings efficiently in positive eccentric annuli than that in concentric annuli. It can be observed in Fig. 10.4.5 that pipe eccentricity has dramatic effect on the MTV for cuttings suspension. It also shows that negative eccentricity is advantageous to efficient cuttings transport. Fig. 10.4.6 demonstrates that the velocities in the smaller section of the eccentric annulus are much lower than those in the larger section. Thus, the cuttings on the narrow side will experience a much lower drag force than those on the larger side of the annulus,
which leads to the conclusion that negative eccentric annuli can provide a better cuttings transport than that concentric annuli. Positive eccentric annuli will give the worst hole cleaning due to the reduced fluid velocity close to the low-side annular wall.

**10.4.6 Effect of cuttings radial positions**

Cuttings radial position has a dramatic effect on the MTV for both cuttings rolling and cuttings suspension as has been seen in Fig. 8.4.7 for deviated wells. For vertical hole cleaning, the effect of cuttings radial positions on the MTV has been shown in Fig. 7.6.11. When the cuttings are moving towards the central region of the annulus, due to the combination of high fluid velocity and high fluid viscosity, the cuttings experience much higher fluid drag force and fluid lift force. Therefore, a much lower MTV is required to remove the cuttings.

**10.4.7 Cuttings settling velocity profile and transport velocity profile**

The MTV package can be used to predict both the cuttings settling velocity profile and cuttings transport velocity profile, which have been shown respectively in Fig. 10.4.8 and in 10.4.9 for the given fluid velocity for Fluid B. Fig. 10.4.8 shows that cuttings settling velocity close to the wall region is much higher than that in the central region of the annulus, which is obviously due to the higher fluid viscosity in the central region. This is not favourable to hole cleaning because a much higher fluid velocity is required to remove the cuttings close to the wall. However, based on the transport velocity of the cuttings close to the central region of the annulus, the MTV can be much reduced as can be seen in Fig. 10.4.9.

**10.4.8 Definition of the appropriate rheological model**

The MTV package has incorporated all three commonly used fluid rheological models, including power law model, Bingham plastic model and Herschel-Bulkley model. For a given set of fluid viscometer readings, the program calculates the rheological parameters when fitted to the three models using a curve-fitting technique. The corresponding regression coefficients of the viscometer readings to the three different rheological models
are also calculated. Then, the best model to represent the fluid rheological properties can be chosen and used for the subsequent calculations of the fluid annular flow profiles and the MTV.

Analysis of the effect of the different fluid rheological models and fluid viscometer readings on the MTV is now conducted. The drilling parameters for the present analysis are tabulated in Table 10.4.4.

First of all, Bingham plastic model is used to characterise the fluid rheological properties for selective viscometer readings. The four cases considered, include:

a. Using two viscometer readings respectively at the shear rates of 3/6 rpm, 100/200 rpm, and 300/600 rpm to derive $\mu_p/\tau_y$;

b. Using all six viscometer readings to derive $\mu_p/\tau_y$ by curve-fitting.

The MTV when using the resultant rheological parameters is then calculated. The results are shown in Table 10.4.5. It can be seen that using different viscometer readings, significantly different MTVs are obtained for both cuttings rolling and cuttings suspension.

Similar calculations have been conducted using power law model, which has been shown in table 10.4.6. It can be seen from the table, that no matter which two viscometer readings are used, the MTVs obtained for both cuttings rolling and cuttings suspension are nearly the same. This demonstrates that by using power law model, more consistent results can be obtained.

The rheogram of the example fluid used is presented in Fig. 10.4.10. In the figure, the different combinations of the viscometer readings used to calculate the fluid rheological properties have been correlated. It can be seen that the rheological properties which result from the application of the Bingham Plastic model will vary considerably depending on the viscometer readings used for the correlation. From the above analysis, the following observations are made:

- Bingham plastic model cannot effectively describe the fluid rheological properties.
Table 10.4.4 Drilling parameters for the study on the definition of the fluid rheology

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annular size (inches)</td>
<td>12.25 x 5</td>
</tr>
<tr>
<td>Hole Angle</td>
<td>60</td>
</tr>
<tr>
<td>Cuttings size (cm)</td>
<td>0.254</td>
</tr>
<tr>
<td>Cuttings density (s.g)</td>
<td>3</td>
</tr>
<tr>
<td>Rotary speed (rpm)</td>
<td>0</td>
</tr>
<tr>
<td>Eccentricity (%)</td>
<td>0.00</td>
</tr>
<tr>
<td>Rate of Penetration (ft/hr)</td>
<td>150</td>
</tr>
<tr>
<td>Viscometer Readings at rpm</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>89</td>
</tr>
<tr>
<td>300</td>
<td>68</td>
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<tr>
<td>200</td>
<td>58</td>
</tr>
<tr>
<td>100</td>
<td>44</td>
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<td>6</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Fluid density (ppg)</td>
<td>8.400</td>
</tr>
</tbody>
</table>

Table 10.4.5 MTV for the definition of the fluid rheology using Bingham plastic model

<table>
<thead>
<tr>
<th>Viscometer Readings Used</th>
<th>MTV (cm/sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rolling</td>
</tr>
<tr>
<td>3 &amp; 6</td>
<td>37.6</td>
</tr>
<tr>
<td>100 &amp; 200</td>
<td>152.1</td>
</tr>
<tr>
<td>300 &amp; 600</td>
<td>59.9</td>
</tr>
<tr>
<td>All Readings</td>
<td>228.6</td>
</tr>
</tbody>
</table>

Table 10.4.6 MTV for the definition of the fluid rheology using power law model

<table>
<thead>
<tr>
<th>Viscometer Readings Used</th>
<th>MTV (cm/sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rolling</td>
</tr>
<tr>
<td>3 &amp; 6</td>
<td>121.8</td>
</tr>
<tr>
<td>100 &amp; 200</td>
<td>136.6</td>
</tr>
<tr>
<td>300 &amp; 600</td>
<td>138.1</td>
</tr>
<tr>
<td>All Readings</td>
<td>131.7</td>
</tr>
</tbody>
</table>
Fig. 10.4.4 Effect of rate of penetration on the MTV for Fluid A

Fig. 10.4.5 Effect of pipe eccentricity on the MTV for cuttings suspension for Fluid A
Fig. 10.4.6 Fluid velocity profile in an eccentric annulus for Fluid A

Fig. 10.4.7 Effect of cuttings radial positions on the MTV for Fluid A (using power law model)
Fig. 10.4.8 Cuttings settling velocity profile in the annulus for Fluid B

Fig. 10.4.9 Cuttings transport velocity profile in the annulus for Fluid B

Fig. 10.4.10 Effect of different viscometer readings on the rheological parameters for Bingham plastic model
• If Bingham plastic model is used to describe the fluid rheological properties, it is crucial to select the appropriate viscometer readings to obtain the fluid yield point and plastic viscosity.

• Power law model can describe fluid rheological properties effectively.

10.5 Limitations of the MTV package

An interactive computer package has been introduced for the predictions of the MTV for effective drilled cuttings transport at various hole angles, pipe rotary speeds and pipe eccentricities. In this section, the limitations of the MTV package are briefly outlined:

10.5.1 Effect of orbital motion on the MTV

Though the effect of drill pipe orbital motion on the MTV has been incorporated into the MTV package, it is correlated only based on the experimental observations using statistic analysis technique. No theoretical studies have been carried out. The user should take the results as a reference only.

It needs to be highlighted that the effect of orbital motion is no doubt one of the most significant parameters to consider when analysing drilled cuttings transport, especially in highly deviated wellbores. However, in actual practices, the orbital rate has not been well understood. More research in the actual rate of orbital motion during normal drilling operations needs to be carried out.

10.5.2 Relative velocity of cuttings

Both cuttings settling velocity profile and cuttings transport velocity profile are based on the theoretical modelling of cuttings settling velocity in dynamic drilling fluids and annular flow of non-Newtonian drilling fluids. The effect of hole angle on the cuttings settling velocity has not been considered. Therefore, the relative velocity of cuttings is only valid for vertical hole cleaning. It can only be taken as a reference when being extended into deviated wells, especially highly deviated wells.
10.5.3 Cuttings bed prediction

In section 10.3, it has been known that in the current package, the prediction of the cuttings bed thickness is based on the assumption that the fluid velocity above the stationary cuttings bed is equal to the MTV for cuttings rolling. But, as a matter of fact, this assumption is not valid based on our purposely designed experiments\(^{(88)}\). The predicted stationary cuttings bed thickness should only be taken as a reference in practice.

10.5.4 Fluid rheological properties

a. For laminar flow regime

Except for the module of Rheogram, the following limitations exist for the MTV package as far as the fluid rheological properties are concerned:

- For eccentric annuli with/without pipe rotation and concentric annuli with pipe rotation, the fluid consistency index \(n\) should be greater than 0.15 when power law model or Herschel-Bulkley model is used to describe the fluid rheological properties.

- No subroutine is available for the predictions of annular flow of Newtonian fluids with pipe rotation. Thus, for Newtonian fluids (\(n=1\) for power law model), the program will crash when the drill pipe rotary speed is greater than zero.

b. For turbulent flow regime

In the present study, the only subroutine which deals with turbulent flow regime is for power law fluid without pipe rotation. If the fluid is not power law fluid in a concentric annuli without pipe rotation, all the calculations are made for laminar flow regime.
CHAPTER 11
GUIDELINES FOR A BETTER HOLE CLEANING
IN THE FIELD

One of the major problems while drilling highly deviated wells is inadequate cuttings transport. In order that a wellbore can be drilled smoothly and safely, the drilled cuttings must be transported up to the surface in a continuous basis. Based on the present studies, some guidelines are recommended for the field engineers to achieve a better cuttings transport, especially while drilling highly deviated wells. Whenever there is any hole cleaning problems, these guidelines may be used as a guide for the field engineer to take the necessary measures to effectively improve the hole cleaning efficiency.

Before the detailed discussions, it needs to be realised that the guidelines are derived based on the present studies with two assumptions:

- Hole cleaning efficiency can be effectively defined by the MTV for cuttings rolling and the MTV for cuttings suspension.
- The higher the MTV, the lower the hole cleaning efficiency.

Based on the two assumptions, it can be easily seen that if changing one parameter increases the MTV, changing this parameter is decreasing the fluid carrying capacity and vice versa.

11.1 Procedure for solving hole cleaning problems

As in any disciplines, before taking any measures, first of all one should identify the problem itself in order to make the effective remedy. It should be kept in mind that whenever there is any hole cleaning problem, the procedure for solving it should be as follows:
Step 1: Identify the nature of the problem

One should try to ask a series of questions and try to answer them so that the nature of the problem can be identified. Some of the hole cleaning related problems are listed as follows:

- A stationary cuttings bed is formed on the low-side annular wall;
- The MTV has been achieved, but the cuttings concentration in the wellbore is too high due to high rate of penetration or penetrated into a sloughing formation etc.
- Cuttings settled and accumulated on the low-side annular wall after stopping mud circulation for a long time due to shut-down inspection, tripping etc.

The most possible problem should be judged based on one's experiences and knowledge so that the nature of the problem can be identified.

Step 2: Get to know the parameters affecting the problem

After identifying the nature of the problem, the various parameters affecting the problem should be listed:

- The depth of the hole cleaning problem;
- Borehole geometry including any possible hole enlargement;
- Possible pipe eccentricity;
- Any orbital motion of the drill pipe;
- Drill pipe rotary speed;
- Cuttings size.

Step 3: Analyse the problem and take the effective measures

After the above discussions, the current situation can be analysed so that the reasons for causing the problem can be identified using one's experiences and the available knowledge. Thereafter, the necessary and effective measures can be taken to improve the hole cleaning condition. For example, if a stationary cuttings bed is formed, one may need to use different sweeps or simply use low viscosity sweep to clear this cuttings bed. In this case, a high viscosity sweep is obviously not effective in removing a stationary cuttings bed.
But, if the problem is that the cuttings concentration is too high due to high rate of penetration, increasing fluid viscosity or reducing the rate of penetration is the most effective way of tackling the problem.

11.2 High fluid flow rate/annular fluid velocity

Fluid velocity is the most important parameter affecting drilled cuttings transport at various hole angles. It is recommended that maximum allowable fluid velocity should be used whenever possible. However, it should be cautious when drilling unstable formations to avoid the possible erosion of the wellbore.

It is recommended that efficient hole cleaning should be set as the top priority during the design of drilling hydraulics because inadequate cuttings transport may cause seriously hole problems such as stuck pipe.

11.3 Avoidance of a stationary cuttings bed/cuttings accumulation

The present experimental data showed that once a stationary cuttings bed is formed on the low-side annular wall, it is very difficult to remove it, especially when highly viscous fluid is used. Therefore, efforts should be always made to avoid the formation of cuttings bed or the accumulation of cuttings in the annulus.

11.3.1 High fluid velocity to avoid bed formation

It is known that when the fluid velocity is below a certain level, a stationary cuttings bed will be formed on the low-side annular wall. In actual drilling operations, it is highly recommended that the formation of a stationary cuttings bed should be avoided. In order to achieve this, the actual fluid velocity should be maintained above the presently defined MTV i.e. the MTV for cuttings rolling or the MTV for cuttings suspension. Whenever possible, the MTV for cuttings suspension should be maintained so that no cuttings will be settled on the low side annular wall.
11.3.2 Enough circulation before stopping the pump

Before stopping the circulation, one should make sure that all the cuttings have been circulated out of the borehole. Otherwise, the cuttings will settle and accumulate on the low-side annular wall once the circulation is stopped. It should be kept in mind that in highly deviated wells, the cuttings may be transporting upward very slowly even when the MTV for cuttings rolling has been achieved. It may take far longer than one thinks to clean all the drilled cuttings out of the borehole.

11.4 Fluid rheological properties

It is well known that fluid viscosity is one of the most important parameters affecting drilled cuttings transport. Its importance has also been stressed by the fact that it is one of the few controllable and adjustable parameters in the field for the improvement of hole cleaning efficiency. From the analysis it is known that the effect of fluid viscosity is quite complicated in nature. The fluid rheological properties should be adjusted according to the different drilling situations concerned.

11.4.1 Fluid rheogram

Before treating the fluid rheology for a better hole cleaning, some pilot tests need to be carried out for two reasons:

- To provide guidance for the different recipes;
- To optimise the treatment i.e. to make the treatment both effective and cost saving.

It needs to be pointed out that simply using the fluid yield point and plastic viscosity to evaluate the performance of a drilling fluid on carrying capacity may be misleading. When comparing different fluids, the fluid rheogram should be used. Curve-fitting technique should be used to derive the best-fit fluid rheological parameters. Then, the performances of the different drilling fluids can be examined. The best treatment can be developed on the basis of effectiveness and cost.
11.4.2 High viscosity fluid

It has been concluded that in concentric annuli, high viscosity fluid can provide the best hole cleaning especially for a smaller annulus while the drill pipe is rotating. Therefore high viscosity fluid is recommended for the following situations:

- The pipe eccentricity is not highly positive eccentric;
- The drill pipe is rotating at a high speed;
- The annular clearance is small.

11.4.3 Low viscosity sweep

Low viscosity fluid is advantageous to cleaning highly positive eccentric annuli and to removing stationary cuttings bed on the low side annular wall. It should be used if:

- The pipe eccentricity is highly positive eccentric;
- A stationary cuttings bed needs to be cleared.

11.4.4 Low viscosity fluid + high viscosity fluid

It is true that both high viscosity and low viscosity fluids can provide efficient hole cleaning in deviated wellbores. For a concentric annulus, high viscosity fluid provided a better hole cleaning than low viscosity fluid. However at a highly positive eccentric annulus, low viscosity fluid is advantageous to deviated hole cleaning. During the cuttings transport experiments, it has also been observed that as long as a cuttings bed is formed on the low side annular wall, it takes much longer time for the high viscosity fluid to clean the bed out of the low side wall than that for the low viscosity fluid. This mainly contributes to the strong turbulence and random flow behaviours of the low viscosity fluid, which made the fluid easily penetrate into the cuttings bed on the low side wall and destabilize the bed there. In order that the cuttings bed can be quickly removed if there is, both concentric section and eccentric part of the deviated borehole need to be well cleaned. Two kinds of fluids with different rheological properties may provide the best deviated hole cleaning efficiency.
When there is any hole cleaning problems, it is recommended that a certain volume of low viscosity fluid is circulated first. The high viscosity fluid is then followed. In this case, the low viscosity fluid can break the cuttings bed and the high viscosity fluid can suspend all the cuttings washed into the fluid flow stream and transport them into the surface.

11.5 Fluid flow profiles

Annular flow profiles are good reflection of the carrying capacity of the drilling fluids. It is a good habit to examine the performances of the different drilling fluids by analysing the fluid flow profiles.

11.6 Hole cleaning at the critical hole angles

40° to 60° from the vertical have been defined as the critical hole angles. Special attention must be paid to the hole cleaning situation at the critical hole angles. For this range of hole angles, two things must be kept in mind all the time:

- It is the most difficult hole angle to be cleaned. Both the present experiments and the previous researches have shown that at 40° to 60° hole angles the minimum transport velocity required to initiate the cuttings in motion is the maximum.
- At these hole angles, a cuttings bed is not only formed on the low side annular wall, but also it will slide downward if the fluid velocity is not high enough.

It is very clear that while cleaning this range of hole angles, the fluid velocity must be higher than that the fluid velocity at which the cutting bed may start sliding downward. Before stopping circulating the drilling fluid, it must make sure that all the cuttings there be cleaned out of the annulus. Otherwise the cuttings accumulated there will slide downward along the low side wall of the deviated annulus. This may easily cause pipe stuck and result in an expensive fishing job.

11.7 Cuttings bed erosion

Once a stationary cuttings bed is formed on the low-side annular wall, it is very difficult to clear it. Based on the present study, there are following methods, which can be used to remove the stationary cuttings bed out of the borehole wall:
11.7.1 Low viscosity fluid in turbulent flow regime

It has been shown that low viscosity fluid in turbulent flow regime is very effective in removing the cuttings bed. It is also effective for transporting the drilled cuttings up to the surface. Low viscosity fluid in turbulent flow regime should be considered when a stationary cuttings bed needs to be cleared. But, calculations need to be made to make sure that the low viscosity pill selected is in turbulent flow regime at the operating conditions, especially for weighted muds. Otherwise, low viscosity pill has no better effect on cuttings bed removal.

11.7.2 High viscosity fluid with pipe rotation

The experiments showed that in order for a high viscosity fluid to clear a stationary cuttings bed, the fluid velocity must be higher than the MTV for cuttings suspension. Otherwise, the bed is difficult to be cleared. If high viscosity fluid is used, rotating the drill pipe may be very helpful for the removal of a stationary cuttings bed, especially considering the possibility of drill pipe orbital motion.

11.7.3 Low viscosity fluid + high viscosity fluid

The combination of low viscosity fluid in turbulent flow and high viscosity fluid in laminar flow is the most effective way of cleaning a stationary cuttings bed out of the borehole. As discussed in section 11.4.3, the low viscosity fluid in turbulent flow will disturb the cuttings bed. Then the high viscosity pill will suspend and transport the cuttings out of the borehole.

11.8 Bigger drill pipe or smaller drill bit

From both the annular flow and cuttings transport studies, it has become very clear that smaller annular size is favourable to drilled cuttings transport. The smaller the annular size, the lower the MTV for the same drilling conditions. From the theoretical analysis for concentric annular flow of Herschel-Bulkley fluids, it is also concluded that at the same drilling conditions, increasing the drill pipe diameter, the shear stress acting on the inner wall of the wellbore will be greatly increased. Accordingly the forces acting on the drilled
cuttings there will be increased. Therefore the MTV required for efficient hole cleaning will be reduced. The hole cleaning can be improved.

In order to achieve the above results, two alternatives are available. One is to increase the diameter of the drill pipe. The second is to reduce the wellbore size i.e. the drill bit diameter. If in a special region hole cleaning has always been a serious problem, a smaller annulus should be considered during the drill string design for once drilling operation has started based on a special drilling programme, it is very difficult to change the drill string structure again.

11.9 Drill pipe rotary speed

Pipe rotation is advantageous to deviated hole cleaning especially in a smaller annulus while high viscosity drilling fluid is used. Drill pipe rotation as part of rotary drilling is the normal and preferred method of drilling even in deviated wells. Whilst sliding with motors virtually no cuttings are removed in practice. Most stuck pipe happens while the drill pipe was not rotating. Whenever there is any hole cleaning problems, rotating the drill pipe is always strongly recommended for the following two reasons:

- Poor hole cleaning may easily cause stuck pipe. Pipe rotation will reduce the risk of stuck pipe.
- Pipe rotation may greatly improve cuttings transport. Therefore the poor hole cleaning situation can be improved. This effect is significant when the drill pipe is rotated orbitally.

Therefore it is always advantageous to rotating the drill pipe.

11.10 Controlled rate of penetration

Rate of penetration will directly increase the load of cuttings in the annulus as shown in Eq. 9.11.1 for vertical annuli. It has been noticed since 1941(1) that the concentration of drilled cuttings should be kept within a limit in order to avoid any hole problems caused by inefficient hole cleaning. In deviated wells, it is expected that the rate of penetration will have a greater effect to the cuttings concentration in the wellbore. It is also envisaged that in
order to avoid hole trouble, the cuttings concentration should be kept within a limit. As stated by Kairon and Schroeter(22), some deviated wells have been most efficiently drilled by controlling the penetration rate below 90 m/hr. It is evident that controlling the rate of penetration within a limit can reduce the overall cuttings concentration within the borehole and reduce the overall load there. As the cuttings concentration increases, the possibility for these cuttings to stick together to form a big cutting will be also increased. When this so called big cuttings have been formed, they may become more difficult to be cleaned out of the borehole and these big cuttings may also start sliding downward at a relatively higher annular fluid velocities, which are not favourable to cuttings transport.

11.11 An increase in fluid density

Increasing fluid density to improve deviated hole cleaning efficiency may not be practicable in some drilling situations. This measure may be necessary in order to get the well drilled and completed smoothly if hole cleaning is the only problem and no other action can be taken instead. Weighted pills are an alternative depending on "leak off" (formation fracturing), the risk of losing circulation and the possibility of differential sticking across a porous zone.

In practice high density sweeps are used to use buoyancy to remove cuttings. It has proved that 16.0 ppg sweeps are effective in hole cleaning.
CHAPTER 12
CONCLUSIONS AND RECOMMENDATIONS

In the preceding chapters, both theoretical and experimental studies on cuttings transport and its related problems have been presented and discussed. In this chapter the conclusions derived based on the present investigations are summarised and recommendations for further research are made.

12.1 Conclusions

Based on the extensive theoretical and experimental studies, the following conclusions are derived:

- A wide range of flow patterns for cuttings transport in deviated wellbores have been observed and defined. Based on these flow patterns, two distinct cuttings transport mechanisms for the removal of drilled cuttings in a deviated annulus have been identified and defined, including the transport mechanism by cuttings rolling and the transport mechanism by cuttings suspension. Accordingly, the MTV required to initiate each of the two transport mechanisms has been defined, which is named as the MTV for cuttings rolling and the MTV for cuttings suspension respectively.

- Deviated wells are more difficult to clean than vertical wells.

- In deviated wells, in order to avoid the formation of a stationary cuttings bed on the low side annular wall, the fluid velocity must be higher than the MTV for cuttings rolling. If the annular fluid velocity is above the MTV for cuttings suspension, no cuttings will settle on the low-side annular wall. However, in vertical boreholes, as long as the fluid velocity can overcome the cuttings settling velocity, the cuttings can be transported up to the surface.
• Two MTV models for the predictions of deviated hole cleaning have been developed based on two classic concepts, including fluid drag force and fluid lift force. Model predictions have showed good agreement with the experimental data. The models have also shown to be in a good agreement with field data.

• As hole angle increases from the vertical, the MTV for cuttings rolling increases until $40^\circ$ to $60^\circ$ has been reached. Then with a further increase in hole angle, the MTV for cuttings rolling decreases.

• For cuttings suspension mechanism, the MTV increases with an increase in hole angle until reaching about $60^\circ$. Thereafter, with a further increase in hole angle, the MTV is essentially the same.

• The worst transport hole angle occurs at $40^\circ$ to $60^\circ$, at which the MTV for cuttings rolling reaches maximum. The cuttings bed may slide down at this range of hole angles as well so that $40^\circ$ to $60^\circ$ have been defined as the critical hole angle.

• In general, the MTV for cuttings rolling is lower than the MTV for cuttings suspension. At low hole angles, cuttings suspension dominates the hole cleaning. In highly deviated wells, cuttings rolling mechanism dominates the cuttings transport.

• In smaller annuli, the MTV for both cuttings rolling and that for cuttings suspension is much lower than that in big annuli i.e. small annuli provide a better cuttings transport than big annuli.

• The effect of fluid rheology on deviated hole cleaning has been shown to be very complex. Both turbulent and laminar flow regime can provide efficient cuttings transport in inclined annuli. For concentric and negative eccentric annuli, high viscosity fluid in laminar flow provided the best hole cleaning and low viscosity fluid in turbulent flow gave a better cuttings transport than the medium viscosity fluid. However in an highly positive eccentric annulus, low viscosity in turbulent
flow regime will give the best deviated hole cleaning. As the fluid viscosity increases, hole cleaning efficiency will be reduced in a positive eccentric annulus.

- It is not necessarily those big cuttings which are more difficult to be cleaned out of the wellbore. Big cuttings may be more readily to be removed instead, which depends on the actual drilling situation.

- An increase in rate of penetration will increase the MTV until reaching 3% cuttings concentration by volume. Then further increasing cuttings concentration has little effect on the MTV.

- An increase in fluid density increases the hole cleaning efficiency.

- Once a stationary cuttings bed is formed on the low-side annular wall, it is very difficult to be cleared when viscous fluid is used.

- Cuttings transport is greatly affected by pipe eccentricity. It has been shown that negative eccentricity provided the best deviated hole cleaning and positive eccentricity provides the worst cuttings transport.

- Drill pipe axial rotation may significantly improve deviated hole cleaning depending on the annular size, the level of fluid viscosity and pipe rotary speed. However, drill pipe orbital motion may dramatically reduce the MTV for cuttings rolling.

- The major factors affecting drilled cuttings transport are annular fluid velocity, hole angle, fluid rheological properties and drill pipe rotation.

- Annular flow profiles have great effect on hole cleaning efficiency. A higher fluid velocity close to the low-side annular wall provides a better cuttings transport than a lower fluid velocity close to the low-side annular wall.

- YP/PV can not reflect the fluid carrying capacity. The fluid rheogram should be examined while analysing the cuttings transport efficiency of the specified fluid.
• Drilling fluid characterisations have showed that the fluid yield point determined by the Bingham plastic model has been much higher than the real yield point.

• Bingham plastic model can not effectively describe the fluid rheological properties. When Bingham plastic model is used, the viscometer readings chosen to derive the YP and PV are quite crucial.

• A new model for cuttings settling velocity in dynamic non-Newtonian drilling fluids has been developed, which has been used for the predictions of the MTV for vertical hole cleaning. It has also been used for the predictions of cuttings settling velocity profile and cuttings transport velocity profile across the entire annulus.

• A MTV computer package has been developed. This programme has incorporated both the MTV models and the annular flow modelling of Herschel-Bulkley non-Newtonian fluids. It has proved to be a very useful tool for the field engineers.

12.2 Recommendations for further research

From the discussions, it has been seen that cuttings transport is a very complicated process. Though great efforts have been made by the author for a better understanding of the cuttings transport mechanisms, some problems are still open for further investigations. Based on the experience by the author, the following recommendations are made for further research activities:

12.2.1 Investigation into the effect of drill pipe orbital motion

The present study has shown that drill pipe orbital motion has significant effect on efficient cuttings transport, especially in highly deviated wells. However, only a limited number of experiments have been reported by the author concerning the effects of drill pipe orbital motion on the MTV for effective cuttings transport. No similar studies have been reported in the literature. In order that the effect of drill pipe orbital motion on hole cleaning efficiency can be well understood and predicted in actual practice, two parallel studies need
to be carried out, including the orbital rate of the drill string in actual drilling operations and theoretical modelling of annular flow of non-Newtonian fluids with orbital motion.

(1) Orbital rate of the drill string in actual practice

Although a series of papers (89-95) have been reported for the analysis of the orbital motion or drill string vibration, no rigorous techniques were available to predict or detect the orbital motion in actual drilling operations. The significance of orbital motion on deviated hole cleaning has highlighted the importance of a better understanding of the orbital motion in actual drilling operations. However, the existence and the level of drill pipe orbital motion in actual practice are not well understood. Considering the level of its effect on deviated hole cleaning, investigation should be initiated to the study of experimentally measuring and theoretically predicting the orbital movement of the drill string.

Obviously, drill pipe orbital motion will cause damage to the drill string and the bottom hole assembly. Drill pipe orbital motion is not desirable from this point of view. However, the significance of orbital motion on hole cleaning efficiency may commend the purposely induced orbital motion for a better cuttings transport, especially for the areas where hole cleaning has been a major concern. The importance of predicting the orbital motion of the drill string lies in the fact that for the troublesome hole cleaning situations, orbital motion may be purposely imposed for a better hole cleaning.

(2) Modelling of annular flow of non-Newtonian fluids with pipe orbital motion

The present experimental data have shown dramatic effect of the drill pipe orbital motion on the MTV for deviated hole cleaning. However, due to the complexity, no efforts have been made by the author on the theoretical modelling of this complicated process. Annular flow of non-Newtonian drilling fluids with drill pipe orbital motion is extremely complicated. As a matter of fact, it is a semi-steady flow. Due to its significant effect on hole cleaning, theoretical modelling of annular flow of non-Newtonian drilling fluids with pipe orbital motion should be attempted. The success of the modelling work may greatly enhance our understanding of the cuttings transport process.
12.2.2 Cuttings bed height predictions and its tolerance in actual practice

Analysis of field data has shown that for large hole sizes, the complete avoidance of a stationary cuttings bed may be not practical. Though the author has proposed a method for the predictions of stationary cuttings bed if there is one, some purposely designed experiments for the measurements of stationary cuttings bed have demonstrated that the assumption made for the prediction of stationary cuttings bed is not valid. That is, for a stable stationary cuttings bed, the fluid velocity above the bed is not equal to the MTV for cuttings rolling.

As a matter of fact, the existence of a stationary cuttings bed will affect the annular flow profiles. Therefore, in order to predict the stationary cuttings bed accurately, modelling of annular flow with a stationary cuttings bed should be initiated. In a parallel study, the fluid velocity required to remove the cuttings just above the stationary cuttings bed should also be investigated. Combining these two studies together, the stationary cuttings bed height can then be predicted accurately.

The predictions of stationary cuttings bed in actual drilling operations are important. It can give us a clear picture about the size of the cuttings bed. However, based on the cuttings bed height alone, the operator can not fully appreciate its significance as long as hole cleaning efficiency is concerned. For example, one may simply ask what is the maximum cuttings bed we can tolerate. As a matter of fact, to predict the size of the cuttings bed is not our objective. Our objective is to understand the hole cleaning situation. Is the present hole cleaning efficiency enough for a trouble-free drilling operation? This is the question we should be able to answer. Simply providing the size of the stationary cuttings bed to the operators is not sufficient. What concerns us most is the critical bed height. The so-called critical bed height is the cuttings bed height, above which we will experience hole cleaning related problems. The attempt to define the critical bed height should be made in parallel with the attempt to predict the stationary cuttings bed height. Otherwise, the operator can not get the maximum benefit from the investigations.
12.2.3 Relative velocity of the cuttings to the fluid

Both the fluid drag force and the fluid lift force acting on the cuttings by the circulating fluid are a function of the relative velocity between the cuttings and the fluid adjacent to the cuttings. This highlights the importance of the study for the relative velocity of the cuttings to the fluid.

In the present theoretical modelling, the relative velocity of the cuttings to the fluid has been taken as the local fluid velocity. This treatment seems to be reasonable for the initiation of cuttings rolling in the sense that for the initiation of cuttings rolling, the cuttings have just started moving upwards. However, the treatment for the initiation of cuttings suspension has been in error because the cuttings have been moving at a reasonably high velocity when the MTV for cuttings suspension is reached. Because of the difficulty of measuring the relative velocity of the cuttings to the fluid, only limited experiments have been conducted in the present study but they were not reported in the thesis.

In order that the MTV models can be further modified, more experiments are very useful for the measurements of the cuttings relative velocity to the fluid, especially for cuttings suspension. The study for the cuttings relative velocity to the fluid will also provide the necessary data base required for the modelling of cuttings transport velocity profile across the annulus in a deviated borehole. Therefore, a new model can be developed to predict cuttings transport velocity for deviated holes so that the exact time required to clean all the cuttings out of the annulus can be easily known.

12.2.4 Effect of cuttings concentration on the MTV

Cuttings are one of the two phases in cuttings transport. The existence of the cuttings in the drilling fluid will obviously affect the annular flow profiles of the fluid. However, in the theoretical modelling, it has been assumed that the cuttings will not affect the fluid properties and its annular flow profiles. It is evident that this is not the true situation. Some rigorous study on the effect of cuttings concentration on annular fluid flow profiles will be useful for a better understanding on the mechanisms of the effect of cuttings concentration
on hole cleaning efficiency. Therefore, its effect on the MTV for efficient cuttings transport can be established from the fundamental flow equations rather than the present statistical analysis.

12.2.5 Effect of pipe eccentricity on the MTV

Effect of pipe eccentricity on the MTV for deviated hole cleaning is very important and complicated. Considering the fact that eccentric annuli are quite common in actual drilling operations, its effect needs to be addressed more extensively. The present experimental data showed that depending on the level of the pipe eccentricity, the effects of fluid rheology on hole cleaning varied significantly. For highly eccentric annuli, the hole can only be properly cleaned using low viscosity pills in turbulent flow regime. However, in concentric annuli, high viscosity fluids in laminar flow are more efficient transport media. Though annular flow of non-Newtonian fluids through eccentric annuli has been addressed by many researchers, the present MTV models have demonstrated that simply based on the annular flow profiles to predict the MTV for efficient cuttings transport, the MTV is overestimated. More rigorous theoretical analysis, perhaps more experiments, needs to be carried out so that the effects of pipe eccentricity can be predicted satisfactorily for both laminar flow regime and turbulent flow regime.

12.2.6 Extensive testing of the MTV models by field data

Though the MTV models have been tested using field data, it is far from enough. More extensive analysis is required to further validate the new MTV models. The analysis should be made for the field data where there are some hole cleaning related problems. In these situations, the MTV models can be used to predict the flow rate required and the predicted flow rate should then be compared against the actual pump rate used in the field. Again, statistical analysis should be carried out so that the limitations of the MTV models can be identified and the MTV models may then be modified accordingly.
12.2.7 Establishment of a data base for cuttings size and size distribution

Cuttings size and size distribution are one of the most important parameters required for the hole cleaning design and analysis in actual drilling operations. The establishment of a data base for the cuttings size and size distribution corresponding to different borehole diameter, formation lithology, bit type etc. will be very useful. It will make the analysis of hole cleaning efficiency much easier. The necessity of collecting cuttings sample before each test run can be eliminated.
Appendix A4.1
Sieve analysis of actually drilled cuttings

Cuttings transport has been investigated since the early 1940s. The effects of cuttings size and shape were studied by many researchers\(^3,7,18\). It is generally accepted that cuttings size and shape affect not only the cuttings settling velocity, but also the orientation of the cuttings during settling such as flatwise, edgewise or both flatwise and edgewise. However until now no results have been reported on the analysis of actually drilled cuttings in size, size distribution and shape.

In fact, whenever talking about cuttings transport experiments or mud carrying capacity design, one may simply ask what size of cuttings should be chosen? How can we consider the influence of cuttings size distribution? This Appendix reports the analysis results of actually drilled cuttings obtained from North Sea which may partly answer the above questions.

A4.1.1 Summary of the simulated cuttings used by previous investigators

In order to study the effects of cuttings characteristics on cuttings transport, a large variety of simulated or actually drilled cuttings, both in size and in shape, have been used by previous researchers, which is listed as follows:

<table>
<thead>
<tr>
<th>Cuttings shape</th>
<th>Cuttings size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>ds=0.15---24.1 (mm)</td>
</tr>
<tr>
<td>Disk</td>
<td>0.1875ds x 0.125---9.7ds x 3.1</td>
</tr>
<tr>
<td>Rectangle</td>
<td>0.458 x 0.419 x 0.063---10 x 8 x 2.1 (mm)</td>
</tr>
<tr>
<td>Square</td>
<td>0.25 x 0.25 x 0.063---1.26 x 1.26 x 0.21 (mm)</td>
</tr>
<tr>
<td>Carthage marble</td>
<td>ASTM 1/4---20</td>
</tr>
<tr>
<td>Actual drilled cutting</td>
<td>ds=0.031---2.62 (mm) or undefined</td>
</tr>
</tbody>
</table>
It should be pointed out that the previous investigators either used single sized simulated cuttings or used actually drilled cuttings which were not defined both in size and in shape. No attempt was made to study the effect of cuttings size distribution. In 1972, Chien(5) discussed the representative diameter of actually drilled cuttings and suggested that in normal drilling operations, the representative diameter should fall between 1/8" and 5/8". Unfortunately no attempt was made to analyse this problem further and only a "guessed" representative diameter range was presented. Apart from the discussion by Chien, no similar analysis has been reported so far.

A4.1.2 Summary of some previous hydraulic transport experiments

During hydraulic transport experiments, apart from studying the effects of solid size and shape, some researchers(51-54) have also studied the effect of solid size distribution. These are summarised in Table A4.1.1.

It is generally regarded that it was those large cuttings which were more difficult to be transported. Therefore the equivalent diameter is usually chosen as $d_{84}$. That is 85% of the cuttings is less than the equivalent diameter. Also from the above, it can be seen that the equivalent diameter must be determined according to the solid size distribution. Thus the necessity of studying the cuttings size and size distribution is further verified.

Table A4.1.1 Representative diameters used for mixed sized particles in hydraulic transport

<table>
<thead>
<tr>
<th>Date</th>
<th>Researcher</th>
<th>Diameters used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>Newitt(51)</td>
<td>$d_{50}$</td>
</tr>
<tr>
<td>1955</td>
<td>Spells(52)</td>
<td>$d_{85}$</td>
</tr>
<tr>
<td>1962</td>
<td>Sinclair(53)</td>
<td>$d_{85}$</td>
</tr>
<tr>
<td>1963</td>
<td>Condolios and Chapus(54)</td>
<td>$d_{wa}$</td>
</tr>
</tbody>
</table>

A4.1.3 Description of the characteristics of cuttings or solid particles

It is easy to see that for a sphere, two parameters will be required to describe its physical properties - its diameter and density. For other shaped particles, more than two parameters
will be required such as in the case of cuttings. Before talking about actually drilled cuttings, it is necessary to discuss how to characterise the irregularly shaped particles. Generally speaking, irregularly shaped and differently sized particles may be simply defined by the following parameters:

a. The equivalent diameter

From cuttings transport analysis it is known that the resistance force for cuttings transport is mainly due to the cuttings weight. Therefore the cuttings diameter, which can be used directly to determine the cuttings weight, will always be important in the transport equations. It is clear that the volume equivalent diameter is the simplest form of diameter which satisfies the above conditions and should be selected. The equivalent volume diameter of a non-spherical particle is defined as the diameter of a sphere which has the same volume as the particle.

However, for the simplicity and practicability, cuttings sieve diameter has been taken as the cuttings diameter. Here a very important definition should be introduced - the sieve diameter $d_{\text{sie}}$, which is defined as the width of the minimum square through which the particle passes. In the following discussions, the cuttings size refers to the cuttings sieve diameter.

b. Density of the particle

This can be satisfactorily determined with a density bottle. In the present case it is not going to be discussed any further.

c. Particle size distribution

Particles such as drilled cuttings are often composed of a range of sizes. By sieve analysis, the particles can be easily divided into different size groups and then the percentage for each group can be determined.
d. **Shape of the particles**

Many definitions have been used to describe the shape of the solid particles such as flaky, fibrous etc. But such terms are very difficult to be quantitatively defined and incorporated into the cuttings transport equations where cuttings shape is involved as a parameter. For simplicity and practicality, the most often used definition to describe the cuttings shape in cuttings transport models is the sphericity:

\[
\psi = \frac{\text{Surface area of a sphere having the same volume as the particle}}{\text{Surface area of the particle}}
\]  \hspace{1cm} (A4.1.1)

Because of the difficulty and impracticability of determining the surface area of the irregularly shaped cuttings, no attempt is made in the present investigations to analyse the shape of the cuttings.

**A4.1.4 Drilled cuttings material and its classifications**

Actually drilled cuttings from ten different wells were provided by Mobil North Sea Ltd. The various drilling parameters are summarised in Table A4.1.2.

It is easy to find that many factors affect cuttings size, shape, and size distribution, including bit type, bit size, weight on bit, rate of penetration, lithology, mud type, mud flow rate, well depth etc. Precisely analysing the cuttings would be impractical using the present technology available. In the present study it is proposed to analyse the cuttings according to different hole size intervals as follows:

<table>
<thead>
<tr>
<th>Hole size: inch</th>
<th>Interval: ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>17-1/2</td>
<td>1500--6000</td>
</tr>
<tr>
<td>12-1/4</td>
<td>6000--12500</td>
</tr>
<tr>
<td>8-1/2</td>
<td>&gt; 12500</td>
</tr>
</tbody>
</table>

For each interval, based on the properties of the lithologies of the formation drilled, three "representative" lithologies are classified such as carbonates, clay or claystone, and sandstone. Generally speaking, the density of carbonates is quite low compared with other kind of cuttings. From the point of view of cuttings transport, it is less important.
Table A4.1.2 Drilling parameters for the cuttings collected for sieve analysis

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Wellbore or bit diameter: in.</th>
<th>17-1/2</th>
<th>12-1/4</th>
<th>8-1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth: ft/to WOB</td>
<td>Depth: ft/to WOB</td>
<td>Depth: ft/to WOB</td>
<td>Depth: ft/to WOB</td>
</tr>
<tr>
<td></td>
<td>Mud type RPM</td>
<td>Mud type RPM</td>
<td>Mud type RPM</td>
<td>Mud type RPM</td>
</tr>
<tr>
<td>1</td>
<td>1525/5683 Gel CMC 30/45</td>
<td>11734 10/60</td>
<td>13070 40</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1550/5620 Gel CMC 4/50</td>
<td>13037 10/55</td>
<td>70/80</td>
<td>60/120</td>
</tr>
<tr>
<td>3</td>
<td>1519/5833 Gel CMC 20/35</td>
<td>11853 20/35</td>
<td>70/120</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1546/5950 Gel CMC 15/55</td>
<td>12840 25/50</td>
<td>80/100</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1585/5941 Gel CMC 5/50</td>
<td>12828 25/60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1520/5871 IOEM 15/50</td>
<td>13247 20/55</td>
<td>80/170</td>
<td>100/180</td>
</tr>
<tr>
<td>7</td>
<td>1890/6060 IOEM 5/50</td>
<td>13268 10/55</td>
<td>14360 20/40</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1645/6620 Caustic 5/45</td>
<td>12549 15/55</td>
<td>40/60</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1650/4060 CMC/Benton. 10/20</td>
<td>11856 30/50</td>
<td>12185 25/35</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1534/5650 CMC/Benton. 35</td>
<td>14800 10/50</td>
<td>16967 25/35</td>
<td></td>
</tr>
</tbody>
</table>

Note: 1. Well No. 1 to 5 are deviated wells and all the others are vertical wells.
2. Well depth: ft; WOB=weight on bit: 1000 lbs
3. IOEM=Interdrill NT
Therefore the carbonates cuttings are not analysed here. In this case, the "representative" lithology groups become "clay or claystone" and "sandstone".

**A4.1.5 Drilled cuttings size distribution**

All the cuttings collected have been sieved using an Octagon 200 sieve shaker and sieves sized from 0.425 mm to 4.0 mm. Before proceeding forward to discussing the sieve results, the weighted average sieve diameter of solid particles is defined as:

\[
\text{d}_{wa} = \frac{\sum \left( \frac{d_i + d_{i+1}}{2} \right) (p_{i+1} - p_i)}{100}
\]  

(A4.1.2)

The various characteristic sizes of the cuttings collected have been summarised in Table A4.1.3. The sieve analysis results are discussed as follows:

(1) **1500 to 6000 ft well interval (bit size 17-1/2")**

The analysis data for the cuttings collected in this well interval are plotted in Figs. A4.1.1 to A4.1.4. From these curves it can be seen that:

a. For those cuttings whose lithology is "claystone", the cuttings sized 1.5 mm have the highest relative percentage by weight. About 15% by weight of the cuttings is larger than 4.5 mm. 85% by weight of the cuttings is less than 4.5 mm. Only 11.62% of the cuttings by weight is larger than 4.0 mm.

b. For "sandstone" cuttings, about 85% of the cuttings by weight is less than 2.4 mm. The cuttings are mainly concentrated on 1.0 mm. Those cuttings whose size is larger than 4.5 mm amount to only about 4%. The weighted average sieve size is 1.45 mm. It is very clear that if we compare the sizes of the two kinds of cuttings at the same cumulative percentage by weight, the "claystone" cuttings are about 1.9 times the size of the "sandstone" cuttings. The percentage of fine cuttings for the "sandstone" is about two times that for the fine particles of the "claystone" cuttings. That is to say that at the same cumulative percentage, the cuttings size for "claystone" is nearly doubled the size for "sandstone". Later we will simply say that the cuttings size for "claystone" is two times the size for "sandstone" and "the same cumulative percentage" is omitted for simplicity. It is
also found that the weighted average sieve size for "claystone" is 1.6 times that for the "sandstone" cuttings.

Table A4.1.3 The various characteristic sieve sizes of the drilled cutting

<table>
<thead>
<tr>
<th>Well interval and Hole size</th>
<th>Lithology</th>
<th>Cuttings sieve size: mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$d_{50}$</td>
</tr>
<tr>
<td>1500-6000 ft 17-1/2&quot;</td>
<td>Claystone</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
<td>1.10</td>
</tr>
<tr>
<td>6000-12500 ft 12-1/4&quot;</td>
<td>Claystone</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
<td>0.90</td>
</tr>
<tr>
<td>Below 12500' 8-1/2&quot;</td>
<td>Sandstone</td>
<td>0.70</td>
</tr>
<tr>
<td>1000-6000 ft Special case 17-1/2&quot;</td>
<td>Claystone</td>
<td>&gt;5.00</td>
</tr>
</tbody>
</table>

(2) 26000 to 12500 ft well interval (bit size 12-1/4"

The cuttings data for this interval are plotted from Fig. A4.1.5 through Fig. A4.1.8. It can be found that:

a. For "claystone", cuttings in the size range of 0.5 to 2.5 mm take almost 25% (relative percentage). Above 3.5 mm, the relative percentage occupied by a particular sized cuttings decreases sharply as the size increases. Those cuttings whose size is larger than 4.0 mm are only 2.4% and for 4.5 mm only 7%. About 85% of the cuttings is less than 3.5 mm. The weighted average size is 2.01 mm.

b. For "sandstone", the cuttings are concentrated around 0.5 mm in size. 54% of the cuttings is less than 1.0 mm. 85% of the cuttings is less than 2.2 mm. The weighted average sieve size is 1.23 mm. It is also found that the cuttings size for "claystone" is about 1.6 times the size for "sandstone" at 85% cumulative percentage. The "average" size, at 50% cumulative percentage, is about 2.3 times larger for "claystone" than that for "sandstone". The weighted average cuttings
sieve for "claystone" is 1.63 times that for "sandstone". It is exactly the same as in the case of 1500 to 6000 ft interval.

(3) > 12500 ft interval (bit size 8-1/2")

In this interval only "sandstone" cuttings were collected. The results are shown from Figs. A4.1.9 and A4.1.10. It is found that about 50% of the cuttings is less than 0.7 mm. 85% of the cuttings is less than 1.6 mm. Only 1% of the cuttings is larger than 3.0 mm. The weighted average cuttings sieve size is 0.92 mm.

(4) Some extreme cases for "claystone" cuttings (1000 to 6000 ft)

Some cuttings collected from the 1000 to 6000 ft interval drilled by 17-1/2" bit are now analysed. The results can be seen in Figs. A4.1.11 and A4.1.12. It is interesting to find that extremely large cuttings do exist during drilling operations. 56.88% of the cuttings is larger than 4.0 mm. Because of the limitation of sieve sizes, the distribution for those which are larger than 4.0 mm is not further analysed. Fortunately this extreme case will only occur in the vertical interval of 1000 to 6000 ft when drilled by a 17-1/2" bit. However particular attention should be given when drilling this interval.

From the above analysis it can be seen that from shallow to deep well intervals, the cuttings size is becoming smaller. From 17-1/2" hole size interval to 12-1/4" hole size interval, the weighted average cuttings size changes from 2.32 to 2.01 mm for "claystone" and from 1.45 to 1.23 mm for "sandstone". The cuttings size reduces by about 15%. The cuttings size for "claystone" is much larger than that for "sandstone".

A4.1.6 Conclusions and recommendations

A4.1.6.1 Conclusions

a. Drilled cuttings are not normally distributed in size. Usually the fine part of the cuttings occupies the higher percentage and the coarse part occupies the lower percentage. But extremely large cuttings do exist during the well drilling process. Fortunately it will only occur for "claystone" in "shallow" well intervals (0 to 6000 ft) where it is usually drilled vertically by 17-1/2" bit.
Fig. A4.1.1 Relative size distribution of "claystone" cuttings from 1500' to 6000' well interval (bit size: 17-1/2")

Fig. A4.1.2 Cumulative size distribution of for "claystone" cuttings from 1500' to 6000' well interval (bit size: 17-1/2")

Fig. A4.1.3 Relative size distribution of "sandstone" cuttings from 1500' to 6000' well interval (bit size: 17-1/2")

Fig. A4.1.4 Cumulative size distribution of "sandstone" cuttings from 1500' to 6000' well interval (bit size: 17-1/2")

Fig. A4.1.5 Relative size distribution of "claystone" cuttings from 6000' to 12500' well interval (bit size: 12-1/4")

Fig. A4.1.6 Cumulative size distribution of "claystone" cuttings from 6000' to 12500' well interval (bit size: 12-1/4")
Fig. A4.1.7 Relative size distribution of "sandstone" cuttings from 6000' to 12500' well interval (bit size: 12-1/4")

Fig. A4.1.8 Cumulative size distribution of "sandstone" cuttings from 6000' to 12500' well interval (bit size: 12-1/4")

Fig. A4.1.9 Relative size distribution of "sandstone" cuttings from below 12500' well interval (bit size: 8-1/2")

Fig. A4.1.10 Cumulative size distribution of "sandstone" cuttings from below 12500' well interval (bit size: 8-1/2")

Fig. A4.1.11 Relative size distribution of "claystone" cuttings from 1000' to 5966' well interval (some extreme cases for bit size: 17-1/2")

Fig. A4.1.12 Cumulative size distribution of "claystone" cuttings from 1000' to 5966' well interval (some extreme cases for bit size: 17-1/2")
b. Cuttings for "claystone" are about 1.9 times as large as those for "sandstone". From the view point of cuttings transport, the transport condition will become much worse when the lithology is claystone than when the lithology is sandstone if all the other drilling conditions are the same.

c. Based on this analysis, the major factors affecting cuttings size are lithology, bit size, and well depth. The analysis has also showed that the present classification of cuttings is reasonable.

d. The cuttings size usually falls below 4.5 mm and the weighted average cuttings sieve size usually falls below 2.4 mm. The representative cuttings diameter range for normal drilling conditions made by Chien was too large (from 3.175 to 14.875 mm). Some researchers used unrealistically large simulated cuttings ($d_s=24.1$ mm).

A4.1.6.2 Recommendations for further study

Further investigation on cuttings size, shape and size distribution may cover the following aspects:

a. Degradation of cuttings while being transported up to the surface

In the next stage the cuttings degradation while being transported up to the surface should be investigated because the size of cuttings collected at the surface is not the real size of the cuttings at the hole bottom.

b. Investigate the cuttings shape characteristics

Cuttings shape is a very important parameter affecting hole cleaning efficiency. Therefore cuttings shape should be further investigated and it should be quantitatively defined so that cuttings shape can be incorporated into the cuttings transport models as a parameter.
Appendix A7.1
Flow equations for turbulent flow of power law fluids through concentric annuli

This appendix presents the various flow equations for turbulent flow of power law fluids through concentric annuli.

A7.1.1 The universal velocity profiles near a rigid wall

a. Within the laminar sublayer

It has been known that the flow in the laminar sublayer is dominated by the viscous stress and the velocity gradient is determined by the molecular viscosity of the fluid. However, in actual practices, the viscous sublayer is usually so thin that the shear stress may be considered constant and equal to the wall shear stress \( \tau_w \). Therefore the velocity variation in the viscous sublayer is usually considered as linear:

\[
u^+ = \left( y_p^+ \right)^{1/n}
\]

(A7.1.1)

where \( u^+ \) is the dimensionless velocity, which is defined as:

\[
u^+ = \frac{u}{u_*}
\]

(A7.1.2)

\( u_* \) is the so-called “friction velocity”, which is defined by:

\[
u_* = \sqrt{\frac{\tau_w}{\rho_f}}
\]

(A7.1.3)

\( y_p^+ \) is the dimensionless distance for characterising the various wall layers and is defined for power-law fluids as:

\[
y_p^+ = \frac{y_p^* \cdot u_*^{2-n} \cdot \rho_f}{K}
\]

(A7.1.4)
b. Within the fully turbulent layer

For the fully turbulent layer, based on the theoretical analysis and the experimental data, Dodge and Metzner\(^{(82)}\) obtained the following expression (after Skelland's correction\(^{(83)}\)):

\[
\frac{u^+}{n^{0.75}} = \frac{2.46}{n^{0.75}} \ln(y_p^+ - \frac{0.566}{n^{1.2}} + \frac{3.475}{n^{0.75}}[1.96 + 0.815n - 1.628n \ln(3 + 1/n)]) \quad (A7.1.5)
\]

It is assumed that there is no transition between the laminar sublayer and the fully turbulent layer. Therefore, the fluid flow jumps directly from the laminar sublayer to the fully turbulent region.

A7.1.2 The various flow equations

a. In the laminar sublayer

From the above analysis, it may be derived that the fluid velocity profile in the laminar sublayer can be expressed as:

\[
u = u^* \left( \frac{\rho_f}{K} \right)^{1/n} \cdot y \quad (A7.1.6)
\]

From Eq. A7.1.6, it can be found that the shear rate in this region can be obtained as:

\[
\frac{du}{dy} = \frac{2.46 \cdot u^* \cdot n}{n^{0.75} \cdot y} \quad (A7.1.7)
\]

b. In the fully turbulent layer

Similarly, the velocity profile is derived as:

\[
u = \left( \frac{2.46}{n^{0.75}} \ln(y_p^+ - \frac{0.566}{n^{1.2}} + \frac{3.475}{n^{0.75}}[1.96 + 0.815n - 1.628n \ln(3 + 1/n)]) \right) u^* \quad (A7.1.8)
\]

The shear rate profile can be obtained as:

\[
\frac{du}{dy} = \frac{2.46 \cdot u^* \cdot n}{n^{0.75} \cdot y} \quad (A7.1.9)
\]

Using the shear rate profile obtained, the fluid viscosity profile can be derived based on the fluid rheological model. So is the fluid shear stress profile derived.
However, it needs to be pointed out that in order to obtain the fluid velocity profile, the fluid friction velocity acting on the borehole and the drill pipe wall should be calculated, which is discussed in Appendix A7.2.
Appendix A7.2

Calculations of the friction velocity and fluid effective viscosity acting on the borehole wall and drill pipe wall

In the calculation of the fluid velocity profile at turbulent flow regime, the friction velocity acting on the drill pipe/borehole walls is required. In this appendix a brief summary is given on how to compute the shear stress and friction velocity on the walls of the borehole and drill pipe.

A7.2.1 The friction factor for concentric annular flow of power-laws

(1) Some basic concepts

i. The equivalent diameter of the annulus

This is the geometric parameter for the conduit based on which a laminar non-Newtonian fluid flow through the conduit would give the same friction factor vs Reynolds number relationship as that for the Newtonian laminar flow through a circular pipe. It is expressed as:

\[ D_{eq} = \frac{4}{3} (r_2 - r_1) \] \hspace{1cm} (A7.2.1)

ii. Effective viscosity of a non-Newtonian fluid \( \mu_e \)

The effective viscosity of a power law fluid in a annular flow is given by:

\[ \mu_e = \frac{k}{3} \left( \frac{1 + 2n}{n} \right)^n \left( \frac{r_2 - r_1}{2v} \right)^{1-n} \] \hspace{1cm} (A7.2.2)

iii. The generalised Reynolds number, \( N_{Re.g} \)

The generalised Reynolds number for any circular conduit is defined as:

\[ N_{Re.g} = \frac{D_{eq} \cdot v_f \cdot \rho_f}{\mu_e} \] \hspace{1cm} (A7.2.3)
iv. The laminar/turbulent transition

The transition from laminar to turbulent flow is determined based on the equation of:

\[ N_{Re,c} = \frac{1117.3}{n^{0.863}} \]  

(A7.2.4)

If the Reynolds number \( N_{Re,g} \) is higher than or equal to the critical Reynolds number \( N_{Re,C} \), the flow is in turbulent regime. Otherwise, the flow is in laminar regime.

v. The critical velocity \( v_c \)

If the annular fluid velocity is known, the flow regime can be also determined by comparing the annular fluid velocity with the critical velocity which is expressed as:

\[ v_c = \left( \frac{139.7 \cdot K}{\rho_f \cdot n^{0.863}} \right)^{\frac{1}{2-n}} \left( \frac{2}{r_2 - r_1} \cdot \frac{1 + 2n}{n} \right)^{\frac{n}{2-n}} \]  

(A7.2.5)

If the fluid velocity is greater than or equal to the critical velocity, the flow is turbulent. Otherwise, it is laminar.

(2) Friction factor calculations for power law fluids

i. Laminar flow regime

The friction factor for laminar power-law fluids through a concentric annulus is calculated by the equation:

\[ f = \frac{16}{N_{Re,g}} \]  

(A7.2.6)

ii. Turbulent flow of power-law fluids

The friction factor correlation for turbulent power-law fluids through a concentric annulus is given by:

\[ \frac{1}{\sqrt{f}} = \frac{1.74}{n^{0.75}} \cdot \ln \left\{ N_{Re,g} \cdot f^{1-n/2} \right\} - \frac{0.343}{n^{1.275}} + 0.305 \]  

(A7.2.7)

A7.2.2 Calculation of the pressure gradient

After the friction factor is calculated, the pressure gradient can be computed by the following equation:
\[ g_p = f \cdot \frac{\rho \cdot v_r^2}{r_2 - r_1} \]  

(A7.2.8)

A7.2.3 The radial position for zero shear rate \( \lambda_0 \)

For power law fluid, the radial position at which zero shear rate occurs is evaluated by:

\[
\int_{\lambda_1}^{\lambda_0} \left( \frac{\lambda_0^2}{\lambda} - \lambda \right) \cdot d\lambda = \int_{\lambda_0}^{1} \left( \lambda - \frac{\lambda_0^2}{\lambda} \right) \cdot d\lambda
\]

(A7.2.9)

where:

\[
\lambda = \frac{r}{r_2} \quad \lambda_1 = \frac{r_1}{r_2} \quad \lambda_0 = \frac{r_0}{r_2}
\]

A7.2.4 The shear stress acting on the borehole/pipe wall

The shear stress acting on the borehole wall is calculated by:

\[
\tau_{bw} = \frac{g_p \cdot r_2}{2} \cdot \left(1 - \lambda_0^2\right)
\]

(A7.2.10)

The shear stress acting on the drill pipe wall is calculated by:

\[
\tau_{pw} = \frac{g_p \cdot r_2}{2} \cdot \left(\lambda_0^2 - \lambda_1^2\right)
\]

(A7.2.11)

A7.2.5 The friction velocity acting on the borehole/pipe wall

After the above calculations, the friction velocity acting on borehole/pipe wall can be obtained as follows:

The friction velocity acting on the borehole wall:

\[
u_{b*} = \sqrt{\frac{\tau_{bw}}{\rho_t}}
\]

(A7.2.12)

The friction velocity acting on the drill pipe wall:

\[
u_{p*} = \sqrt{\frac{\tau_{pw}}{\rho_t}}
\]

(A7.2.13)
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