Chapter 5

COUPLING OF CAPILLARY, GRAVITY, AND VISCOUS FORCES

5.1 Introduction

We have so far examined how the interaction between capillary and gravity forces generate distinctive sets of multiphase flow displacement responses that result in a range of saturation and trapping patterns. However, multiphase flow is generally characterised by the interactions of at least three forces: capillary, gravity, and viscous forces. The justification for ignoring viscous forces in all previous simulations is provided by the assumption of slow injection rates. But in most multiphase flow situations of practical interest gravity forces play an important but secondary role. The effect of viscous forces is likely to be dominant during drainage and imbibition displacement processes in tight or thin porous media, in high rate flow near wells, in large scale systems with low vertical communication ($K_v/K_h$), and during most routine laboratory tests for the determination of multiphase flow properties e.g. relative permeability. In the present chapter we explore the characteristic features of the response of multiphase flow under non-negligible viscous pressure gradients and the dependency of such responses on a number of system variables like fluid viscosity, interfacial tension, and system scale. Some of the previous models simulated under capillary and gravity are revisited and re-instantiated at varying injection rates to examine the broad features of multiphase flow under the simultaneous action of capillary, gravity, and viscous forces. A select set of immiscible displacement experiments by Lenormand et al (1988) are reproduced to demonstrate the predictive power of the capillary-viscous force coupling approach used in the network model. But first, a targeted parametric sensitivity study of the effect of injection rate on flow regime under zero gravity force and at varying viscosity ratios is presented in order to demonstrate the main features of the model and to illuminate the basic pore scale mechanisms that underpin viscous-driven regime transitions.
5.2 Viscous-Driven Regime Transitions

In multiphase flow displacement involving two or more fluid phases of different viscosities, differential dynamic pressure gradients are set up within each phase, and depending on the magnitude of the global pressure gradient imposed across the entire flow domain a wide range of displacement patterns can be created. Dynamic pressure gradients are often referred to as viscous forces and generally increase with flow velocity or injection rate. The governing flow equations that couple capillary, gravity, and viscous forces have already been presented in Chapter 3. Here we investigate the implications of such a coupling under varying injection rates.

5.2.1 Regime Transitions under an Adverse Viscosity Ratio

We consider injecting CO₂ at different rates into an initially H₂O-saturated network, and with gravity forces turned off. The viscosity ratio under the chosen temperature and pressure conditions of 35°C and 1500psia, respectively, amounts to about 17 \( \frac{\mu_{H₂O}}{\mu_{CO₂}} = M = \frac{[1.0e-3PaS]}{[5.82e-05PaS]} \). A viscosity ratio, \( M \), greater than 1.0 is conventionally described as adverse or unfavourable for reasons we shall shortly see. All networks used in this section have a mean pore (bond) radius of 20\( \mu \)m, a PSD variance of 75 (\( R_{min}=5\mu m, R_{max}=35\mu m \)) and dimensions of 131x75x1 (consisting of 29625 bonds). A constant porelength of 300\( \mu \)m was assumed at full network connectivity (2DZ=4), whilst mass transfer via molecular diffusion was disabled. CO₂ injection was at a single point located at the centre of the inlet face of the network. Figures 5-1 shows a schematic of the orientation of the global viscous pressure gradient relative to the axis of the network.

![Figure 5-1: Schematic of the orientation of the global viscous pressure gradient in relation to the network axes.](image-url)
Results

Figure 5-2 shows a progressive but non-linear response of the displacement pattern to varying injection rate. A transition from capillary fingering to viscous fingering in the general direction of the global pressure gradient ($\Delta P_{\text{vis} \text{global}}$) as injection rate increases can clearly be observed. The non-linearity of the change in flow pattern to the increase of viscous pressure gradient with injection rate arose because $\Delta P_{\text{vis} \text{global}}$ had to cross a critical threshold that is governed by the characteristic capillary pressure distribution in the network before viscous forces begin to significantly affect flow behaviour. Once this critical threshold had been crossed, the influence of the viscous force accelerated rapidly, creating highly streamlined displacement channels that bypass the bulk of the host brine, hence the adverse viscosity ratio. These flow channels are commonly called viscous fingers.

Fingering is controlled by at least three factors. The first is local variation of pressure gradient across individual pores caused by differences in pore hydraulic radii. The second is the pore orientation – flow velocity in pores oriented parallel to the direction of the global pressure gradient is generally higher. The third concerns the viscosity ratio between the injected (or invading) phase and the defending phase – the magnitude of pressure drop across a phase for a given flow velocity is proportional to its viscosity but it is the differences in pressure drop distribution in one phase relative to the other that either inhibits or facilitates fingering. Since the host phase (water) is in this case more viscous, pressure gradients will generally be steeper in it. This has crucial implications for the local velocity of advance of the CO$_2$-water interface.

At slow rates (5.97E-12 - 5.97E-11 m$^3$/sec), viscous forces are small and only in a handful of untrapped pores at the perimeter of the gas cluster – likely only one – would the gas-
water meniscus be in motion at any point in time. The interface therefore advanced in mostly one pore at a time along a random path that traced the distribution of pores with the smallest entry capillary pressures. This stepwise character of drainage at low injection rates approximates to a classic invasion percolation process. As injection rate increases so does the magnitude of the local viscous pressure gradient across the interface and multiple perimeter pores could therefore be invaded simultaneously. However, pores oriented parallel to $\Delta P_{vis}^{global}$ (y-bonds) broadly had higher net driving forces than pores perpendicular to it (x-bonds) although bond hydraulic conductivities would significantly modify the local viscous pressure orientations (see Figure 5-1). Thus, although perimeter pores were sequentially invaded in all directions with continued injection, the balance of flow tended towards the vertical direction.

Figure 5-3 shows important stages in the formation of a viscous finger. Shortly after the onset of injection, the early stages of viscous finger formation could clearly be discerned.

The natural bias of pressure drop along the vertical direction that initiated fingering was strengthened as the finger grew. As the leading invasion front approached the outlet boundary of the network, viscous pressure gradients across the perimeter water pores became steeper – given the relatively smaller pressure gradients in the lighter CO$_2$ phase a large pressure drop across the bank of water that separated the tip of the advancing finger and the outlet pores (where the lowest pressures in the network occur) was required to satisfy the imposed boundary condition. Figure 5-4 illustrates a schematic of viscous pressure distributions as a function of the distance of the leading invasion front from the inlet under adverse viscosity ratio at varying injection rates, whilst Figure 5-5 shows the viscous pressure distributions in the network at selected stages during the development of a viscous finger. The narrower this water bank, the steeper the pressure
gradient across it, and perimeter pores at or near the leading front became the preferred sites for invasion. Hence, once viscous fingering has been initiated it would tend to accelerate.

Figure 5-4: Schematic of the viscous pressure profile as a function of the distance of the leading invasion front from network inlet for a high rate injection at an adverse viscosity ratio. The points of abrupt change of slope represent capillary pressure drop at the interface. Time increases from \( t_1 - t_4 \).

Figure 5-5: Average bond pressure distributions (a), and local absolute viscous pressure gradient distributions (b), during the evolution of a viscous finger. In (a), bond pressures decrease from inlet to outlet, reflecting the global pressure gradient orientation. In (b), the largest absolute local pressure drops occur, broadly, within pores of the more viscous defending phase (not distinguished here) that are ahead of the advancing finger (also see Figure 5-4).

The characteristic shape of the \( S_{gc} \) vs. Rate curve, Figure 5-6, reemphasises the non-linear nature of the transition from a capillary to a viscous fingering regime. Although this transition was usually associated with a decrease in displacement efficiency (or \( S_{gc} \)), Figure 5-6 shows that the decline in \( S_{gc} \) as a result of fingering was only temporary. As injection rate increased, \( S_{gc} \) decreased from a high plateau through a short but steeply sloping transition region and then reaches a minimum once a critical injection rate was reached. Increase of rate beyond this critical value led to the reversal of the downward
trend of the $S_{gc}$ profile, and it started to increase once again, eventually reaching the initial maximum under capillary fingering. Figure 5-2(v-vii) shows that the fingered pattern persisted as injection rate increased above the value that corresponded to the minimum $S_{gc}$ in Figure 5-6 but the size of the average flow channel became larger and this helped to enhance displacement efficiency. To explain this result we must recall the basic coupling equation of capillary and viscous forces that was given in Chapter Three and here restated as Equation (5-1).

$$\Delta P_{Net}^i = \Delta P_c^i + \Delta P_{vis}^i$$

(5-1)

where, $\Delta P_{Net}^i$ is the positive net local driving pressure during drainage, $\Delta P_c^i$ is the net local instantaneous capillary pressure, $\Delta P_{vis}^i$ is the local viscous pressure drop across perimeter pore $i$.

$$\Delta P_c^i = P_g - (P_l + P_{ic}^i)$$

(5-2)

where, $P_g$ is the absolute pressure of the gas phase, $P_l$ the absolute pressure in the liquid (water) evaluated at the upper boundary of the network, $P_{ic}^i$ the static equilibrium capillary entry pressure.

At low rates $\Delta P_c^i$ is small but of the same order of magnitude as $\Delta P_{Net}^i$, whilst $\Delta P_{vis}^i$ is relatively negligible. Only in a few pores will $\Delta P_{Net}^i$ be positive and a capillary dominated IP-like gas expansion occurs.

At high rates, $\Delta P_{vis}^i$ increases and becomes of the same order of magnitude as $\Delta P_{Net}^i$, whilst $\Delta P_c^i$ remains largely unchanged from the its original value under capillary dominated regime – despite injecting more mass of gas per unit time, $\Delta P_{vis}^i$ is just

Figure 5-6: $S_{gc}$ as a function of injection rate under an adverse viscosity ratio of 17.
sufficient to drive gas expansion without leading to the rise of $P_g$. Many perimeter pores will have net positive $\Delta P^i_{Net}$ but the absolute magnitudes will be distributed based on the proximity to the leading front – higher near the leading front and lower at the lagging front. This phase of gas evolution is characterised by a highly inefficient viscous fingering regime.

At ultra-high rates, $\Delta P^i_{vis}$ increases still further and would be of a similar order of magnitude as $\Delta P^i_{Net}$. But now $\Delta P^i_c$ also starts to increase because the prevailing $\Delta P^i_{vis}$ is insufficient to expand the gas fast enough to keep $P_g$ from rising. Thus the directed fingered flow pattern is accompanied by an additional lateral expansion driven by the increase in the average $\Delta P^i_c$.

Figure 5-7 shows a plot of the maximum local ratio of $\Delta P^i_{vis}$ to $\Delta P^i_c$ ($Ca^* = \Delta P^i_{vis}/\Delta P^i_c$) as a function of PVI during CO$_2$ evolution at varying injection rates. $Ca^*$ is similar to the familiar microscopic capillary number but they are not exactly the same thing. Indeed, $Ca^*$ increased linearly with increase in injection rate from 5.97e-12 m$^3$/s to 5.97e-7 m$^3$/s just as the customary $Ca$ ($\Delta P^i_{vis} \bar{f}/2\sigma$) would behave i.e. every increase of $Ca^*$ was virtually caused by the increase in $\Delta P^i_{vis}$, with $\Delta P^i_c$ remaining virtually constant. For a comparison of the profiles of $Ca^*$ and $Ca$ at equivalent injection rates see Figure 5-8, which also includes a plot of the ratio $Ca^*/Ca$ for varying injection rates.

**Figure 5-7:** Maximum local ratio of $\Delta P^i_{vis}$ to $\Delta P^i_c$ ($Ca^*$) as a function of PVI at different injection rates.
Figure 5-8: Plots of (a) the maximum local microscopic $Ca$ as a function of PVI, and (b) the ratio of $Ca^*$ to $Ca$ as a function of PVI, at different injection rates.

As injection rate increases further (5.97e-6 m$^3$/s and above), $Ca^*$ still increased proportionately but rose to plateau values more gradually (Figure 5-7). There was a brief transition period at the onset of injection when, compared to evolution behaviour at lower rates, the absolute pressure of the invading phase – as specified by its compressibility properties, made a substantial contribution to the net pressure driving the displacement process and caused the embryonic cluster to spread out more laterally than would have been the case if $\Delta P^i_c$ were negligible. And although the contribution of $\Delta P^i_c$ to the displacement process fades out once this transition phase has passed, subsequent displacement behaviour was inadvertently affected by the characteristic frontal pattern laid down during this initial phase of evolution.

This non-monotonicity in the response of displacement efficiency to increase in injection rate was also predicted by the model of immiscible displacement in porous media presented by Lenormand et al (1988), and it is therefore not a bug of the modelling approach used here but rather a feature of displacement under an adverse viscosity ratio. The extent to which the description of the phenomenon by the current model aligns with physical reality could be definitively determined by well calibrated experiments.

Figure 5-9 shows the result of simulations in which the viscous pressure gradient coupling ($\Delta P^i_{vis}$) was disabled, leaving $\Delta P^i_c$ as the sole pressure driving the displacement. Comparison with Figure 5-2 shows that at slow injection rates the displacement patterns
were identical. But as injection rate increased, models with no viscous coupling displayed frontal advance behaviour which was in stark contrast to the fingering behaviour observed in equivalent models that incorporate viscous pressure gradients in Figure 5-2. The lesson here is that the incorporation of viscous forces in the simulation of immiscible displacement at high injection rates is not optional. We shall soon see why the coupling approach adopted here is consistent with the physics of drainage in porous media.

\[
\begin{array}{cccccccc}
Q \text{ [m}^3/\text{sec}] & 5.97 \times 10^{-12} & 5.97 \times 10^{-11} & 5.97 \times 10^{-10} & 5.97 \times 10^{-9} & 5.97 \times 10^{-8} & 5.97 \times 10^{-7} & 5.97 \times 10^{-6} \\
\end{array}
\]

Figure 5-9: Regime transition with varying injection rate under an adverse viscosity ratio, M, of 17, with the viscous pressure coupling disabled (compare with Figure 5-2 which incorporates viscous pressure coupling).

5.2.2 Regime Transitions under a Favourable Viscosity Ratio

The viscosities of the invading and defending phases are now reversed and the new viscosity ratio, M, becomes 0.0582. We maintain the assumption of the defending phase as the wetting phase.

An increase in injection rate led to a transition from capillary fingering to a more stable frontal advance, Figure 5-10.

\[
\begin{array}{cccccccc}
Q \text{ [m}^3/\text{sec}] & 5.97 \times 10^{-12} & 5.97 \times 10^{-11} & 5.97 \times 10^{-10} & 5.97 \times 10^{-9} & 5.97 \times 10^{-8} & 5.97 \times 10^{-7} & 5.97 \times 10^{-6} \\
\end{array}
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Figure 5-10: Viscous-driven regime transition with varying injection rate (at a single point near the bottom) under a favourable viscosity ratio, M, of 5.82E-2.

At low injection rates, displacement was still by the classic invasion percolation process, where at any instance – because of low global viscous pressure gradient, only in very few pores would the local pressure gradient exceed the capillary entry thresholds. The final
saturation distribution again traced the distribution of bonds with the smallest capillary pressures in the network, Figure 5-10(i-iii).

The rise in $\Delta P_{vis}^{global}$ that accompanied an increase in injection rate made local capillary pressures less influential and therefore more and more perimeter pores were open for invasion. It is reasonable to expect the most conductive pores (which are also oriented in the direction of the global pressure gradient) to fill first at the onset of displacement, creating a temporary local finger and a leading front. But the perimeter pores around this leading front did not become the preferred sites of subsequent immediate invasion events and thereby propagate the finger in the same manner when $M>1$, and Figure 5-11 (which shows a schematic of typical viscous pressure distributions as a function of the distance of the leading front from the inlet for $M < 1.0$) helps us to explain why. Because viscous pressure gradients were much steeper in the more viscous invading phase, the further the fluid/fluid interface moved away from the inlet the more gradual was the viscous pressure gradient on the defending phase side of the interface and the steeper the gradient on the invading phase side of the interface (Figure 5-11). Net driving pressure therefore decreased away from the inlet and this checked further immediate propagation of the leading front in preference to the lagging fronts. This not only explains the spreading out of the displacement front quite early on, but also the development of a piston-like invasion front once the invading phase has formed a hydraulic continuum between the lateral boundaries of the network.

![Figure 5-11: Schematic of the viscous pressure profile as a function of the distance of the leading invasion front from network inlet for a high rate injection at a favourable viscosity ratio. The points of abrupt change of slope represent capillary pressure drop at the interface. Time increases from $t_1 - t_4$. $S_{gc}$ increased with injection rate (Figure 5-12) but still non-linearly because of the finite capillary pressure drop that must be incurred across the interface.](image-url)
Figure 5-12: $S_{gc}$ as a function of injection rate under a favourable viscosity ratio of 5.82E-2.

Figure 5-13 shows the impact of turning off the viscous pressure coupling on regime transitions under a favourable viscosity ratio. Compared to Figure 5-10 which incorporates the full effect of viscous forces, ignoring the viscous pressure coupling tends to underestimate the displacement efficiency at intermediate injection rates.

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Figure 5-13: Regime transition with varying injection rate under a favourable viscosity ratio, M, of 5.82E-2, with the viscous pressure coupling disabled (compare with Figure 5-10 which incorporates viscous pressure coupling).

### 5.2.3 Regime Transitions under an Increasing Viscosity Ratio

Departures of viscosity ratios from the two previous scenarios have been considered.

An increase of M from 1 to 1718 (by increasing defending phase viscosity whilst keeping that of the invading phase constant) intensified the fingering response for the same injection rates, Figure 5-14. As defending phase viscosity increased, larger global pressure gradients were required to flow at the same rate and thus the capillary pressure played a diminishing role, just as an increasingly larger percentage of the total viscous pressure drop across the network now occurred within the heavier (defending) phase (Figure 5-15). This imposed larger net driving pressures on perimeter pores as the viscosity ratio increased, and displacement became increasingly dominated by viscous fingering.
The $S_{gc}$ profile (Figure 5-16) underwent marked changes as $M$ increased: for $M=1$, the $S_{gc}$ profile increased monotonically, albeit non-linearly, as injection rate increased; for $M=17$, the drop in $S_{gc}$ due to transition from capillary fingering to viscous fingering was reversed as injection rate continued to increase and $S_{gc}$ eventually rose to the levels attained under capillary regime; for $M=1718$, $S_{gc}$ decreased broadly whilst the later reversal of the curve at higher rates, as seen for $M=17$, was milder and quickly stabilized at an $S_{gc}$ value 3 times smaller than the $S_{gc}$ value under capillary regime (Figure 5-16).

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Figure 5-14: Viscous-driven regime transition with varying injection rate (at a single point near the bottom) under varying adverse viscosity ratios. $M=1$ is strictly not adverse but included here for comparison purposes.

Figure 5-15: Schematic of the viscous pressure profile with respect to a fixed distance of the leading front from the inlet for a high rate injection and under varying adverse viscosity ratios. The points of abrupt change of slope represent capillary pressure drop at the interface.
Figure 5-16: $S_{gc}$ as a function of injection rate at varying adverse viscosity ratio. M=1 is strictly not adverse but included here for comparison purposes.

Having described in some detail the pore level causal chain of events that give rise to the observed regime transitions at the macroscopic (network) level under varying viscous-capillary force ratios and with zero gravity force, we next examine the impact of non-negligible gravity gradients on the nature of regime transitions under concurrently varying gravity and viscous forces.

### 5.3 Displacement Behaviour under Varying Viscous and Gravity Gradients

Situations in which the impact of either one of the three forces (capillary, gravity, or viscous) on multiphase flow behaviour can be entirely eliminated are rare. Although it is always possible to identify a subset of the forces as contributing the most to the overall flow behaviour this may not mean that the action of the other forces can be completely neglected. Failing to properly account for the interactions between the possible governing forces make analysis of multiphase flow behaviour less unique and therefore less useful. This section examines the nature of these interactions under a range of system configurations.

The magnitudes of gravity and viscous forces were varied by varying the gravitational acceleration (i.e. $g$) and the injection rate, respectively. The choice of these parameters ensures that one of the forces can be varied somewhat independently of the other. The same network properties and operating conditions as used in the previous sections are employed here but injection is now across the full face of the network.

#### 5.3.1 Results and Discussion

The effect of gravity on multiphase flow is strongly dependent on its orientation relative to the dominant flow direction. Therefore, three gravity-viscous force configurations were...
considered, namely: gravity destabilised (gravity parallel to and in the same direction as viscous force), gravity stabilized (gravity directly opposing viscous force) and edge gas injection (gravity perpendicular to viscous force).

5.3.1.1 Gravity Destabilised Injection Configuration

Figure 5-17 shows a schematic of the global orientations of the principal forces relative to the axis of the network, whilst Figure 5-18 shows injected gas at the point of breakthrough displaying various displacement patterns in response to the relative influence of capillary, gravity, and viscous forces. In Figure 5-18 the gravitational force (denoted by g) increases from the top row to the bottom row whilst viscous force (denoted by $Ca = Q\mu/\sigma A$) increase from left to right.

Given the adverse viscosity ratio, and the density contrast between CO$_2$ and water, under a gravity destabilized displacement configuration, increasing either the injection rate or the gravitational acceleration (a cipher for model height) can be expected to result in a transition from a capillary dominated flow to either viscous or gravity fingering. This can clearly be observed in Figure 5-18(a, b, and c). Concurrent increase of both gravity and viscous forces led to intensification of the fingering process – more vividly observed in column three: a-iii to c-iii, and row two: b-i to b-iii, of Figure 5-18. Fingered displacement, however, ceased once a sufficient gravity gradient exists for a transition to a dispersive migratory flow. The bottom row of Figure 5-18 shows that once migratory flow has started, an increase in injection rate did not lead to the streamlining of the flow as in the non-migratory phase but rather tended to make flow more dispersed.

Fingering during displacement generally consists of, from a geometrical point of view, the narrowing of the flow channel. But Figure 5-18 shows that increasing either of the fingering-inducing forces (gravity or viscous) indefinitely may not lead to an indefinite narrowing of the flow channel. After a certain level of fingering has been achieved, a point was reached beyond which increasing the driving force caused a transition in the nature of flow instability. This transition was dependent on the dominant driving force and can be used to distinguish between gravity-driven and viscous-driven flow instabilities.
For gravity-driven instability, increasing the gravitational force caused a transition from gravity fingering to migratory flow Figure 5-18(c-d) – the mechanism by which this occurs has been discussed extensively in the previous chapter. For viscous-driven instability on the other hand, increasing the viscous pressure gradient beyond a point where a distinct viscous finger could already be identified led to the creation and propagation of additional fingers – usually of widths that were comparable to that of the fewer number of fingers before the transition (Figure 5-18[a, b, c]-iv to [a, b, c]-v). Multiple finger formation was indicative of the dominance of viscous forces over capillary and gravity forces (in non-migratory regimes) – the increased viscous pressure gradient was, however, complemented by the momentary rise in invading phase pressure in driving the meniscus into a larger number of pores simultaneously (see section 5.2.1 for a full explanation).

Regime transitions at very high gravity or viscous gradients led to enhanced displacement efficiency. Since $S_{gc}$ has proven to be a fairly good measure of displacement efficiency, Figure 5-19 shows the surface topology of $S_{gc}$ variation as a function of gravity ($g$) and viscous forces from two observational perspectives. The $S_{gc}$ surface is described by a valley (minimum $S_{gc}$ values on the surface corresponding to viscous and/or gravity fingering regimes) that is bordered by two peaks (maximum $S_{gc}$ values on the surface), with one peak marking the intersection of high viscous and gravity forces (viscous perturbed migratory regime), and the other marking the intersection of low gravity and low viscous forces (capillary dominated regime).

Figure 5-17: Schematic of the orientation of the global viscous and gravity pressure gradient in relation to the network axes under a gravity destabilised injection configuration.
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Figure 5-18: CO₂-H₂O regime transitions under co-aligned viscous and gravity gradients for a gravity destabilised injection configuration.
5.3.1.2 Gravity Stabilised Injection Configuration

In this configuration gravity and viscous forces act in opposite directions (see Figure 5-20 for a schematic representation of force orientations relative to the axis of the network). It is rather like injecting across the top face of a vertical core plug of varying heights, at different rates. It should be obvious why the first row of Figure 5-21 is identical to the first row of Figure 5-18 turned upside down. Figure 5-21 shows that gravity acted to dampen both capillary and viscous fingering, and that the greater the gravity gradient the greater the damping effect produced. From a gravitational acceleration of 10 (corresponding to a notional network height of 40cm) and above, piston-like displacement could be observed even at the highest injection rate considered. The surface chart of $S_{gc}$ as a function of $g$ and $Ca$ (Figure 5-22) exhibits a somewhat flat inclining profile with the highest points corresponding to the largest gravity force considered.
Figure 5-20: Schematic of the orientation of the global viscous and gravity pressure gradient in relation to the network axes under a gravity stabilised injection configuration.

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Figure 5-21: CO$_2$-H$_2$O regime transitions under co-varying viscous and gravity gradients for a gravity stabilised injection configuration.
5.3.1.3 Edge Injection Configuration

Here, the gravity force is perpendicular to the viscous force (Figure 5-23). The general trend was for gravity to cause CO₂ to override the brine, leading to an overall decrease in displacement efficiency (Figure 5-24). This was despite the fact that compared to the other injection configurations, edge injection models incorporate the smallest absolute gravity gradient – the models here span a vertical distance that is 42% shorter than in the models used for previous injection configurations. Unlike in the previous configurations, however, the detrimental effects of very high gravity gradients on displacement efficiency under the edge injection configuration were more effectively suppressed by increasing the injection rate (Figure 5-24 [c and d]). Figure 5-25 shows the characteristic response of the S_{gc} surface chart with variation in Ca and g.

Figure 5-22: CO₂ S_{gc} surfaces from two observational perspectives generated from regime transitions due to co-variation of viscous and gravity forces for a gravity stabilised injection configuration
Figure 5-23: Schematic of the orientation of the global viscous and gravity pressure gradient in relation to the network axes under an edge injection configuration.

<table>
<thead>
<tr>
<th>Ca</th>
<th>1.86E-09</th>
<th>1.86E-08</th>
<th>1.86E-07</th>
<th>1.86E-06</th>
<th>1.86E-05</th>
</tr>
</thead>
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<td><img src="a-ii" alt="Image" /></td>
<td><img src="a-iii" alt="Image" /></td>
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<td><img src="b-ii" alt="Image" /></td>
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<tr>
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<td><img src="d-ii" alt="Image" /></td>
<td><img src="d-iii" alt="Image" /></td>
<td><img src="d-iv" alt="Image" /></td>
<td><img src="d-v" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 5-24: CO₂-H₂O regime transitions under co-varying viscous and gravity gradients for an edge injection configuration.
Chapter 5 – Coupling of Capillary, Gravity, and Viscous Forces

Figure 5-25: CO₂ $S_{gc}$ surfaces from two observational perspectives generated from regime transitions due to co-variation of viscous and gravity forces for an edge injection configuration

5.4 Impact of varying IFT at Varying Injection Rate

IFT is a parameter whose variation can simultaneously alter the capillary-gravity-viscous force balance. We examine the nature of these transitions in the context of changing injection rate.

Two sets of simulations have been performed, both using an edge injection configuration. The first set assumes gravity force to be zero and the second incorporates the effect of gravity.

5.4.1 Results at Gravitational Acceleration=Zero

As IFT was decreased, the influence of viscous forces increased for the same injection rate (Figure 5-26), and increasing the injection rate accentuated the viscous effect. But the increasing viscous influence with decrease in IFT did not result in the familiar fingering displacement pattern. Instead, the main effect of the decrease in capillary pressure –
which a decrease of IFT implied – was the suppression of both capillary and viscous fingering.

As IFT decreased, both the capillary entry threshold and the viscous pressure gradient (Figure 5-27) decreased. From the perspective of the capillary entry threshold, a decrease in IFT at a given injection rate increases the chances for a CO₂ meniscus to invade multiple pores simultaneously rather than moving into one pore at a time, hence limiting capillary fingering. At low injection rates, the generally reduced viscous pressure gradient is diminished further as IFT decreases and this inhibits the initiation and propagation of viscous fingers. The result is a transition from capillary fingering at high IFT to frontal advance at low IFT for low injection rates (Figure 5-26[a-i to c-i]). As the viscous pressure gradient increases with injection rate, viscous fingering kicked in but the intensity of fingering became increasingly reduced as IFT decreases.

Thus, at a constant adverse viscosity ratio the largest IFT considered produced the customary transition from capillary fingering to viscous fingering as injection rate increased, whilst for the lowest IFT considered the transition was from a piston-like displacement to viscous fingering. Two important conclusions may be immediately drawn. Firstly, viscous fingering is strongly mediated by the magnitude of the interfacial tension, and secondly, given a constant viscosity ratio the capillary number (as commonly formulated) is not sufficient to uniquely predict the flow regime under different combinations of IFT and injection rate (Figure 5-26).
<table>
<thead>
<tr>
<th>IFT, mN/m</th>
<th>Q, m³/s</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
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<tr>
<td>27.6</td>
<td>5.97E-12</td>
<td>5.97E-11</td>
<td>5.97E-10</td>
<td>5.97E-9</td>
<td>5.97E-8</td>
</tr>
<tr>
<td>2.76</td>
<td>a-i: 1.86E-09</td>
<td>a-ii: 1.86E-08</td>
<td>a-iii: 1.86E-07</td>
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<td>b-ii: 1.86E-07</td>
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<td>b-iv: 1.86E-05</td>
<td>b-v: 1.86E-04</td>
</tr>
<tr>
<td>Ca</td>
<td>c-i: 1.86E-07</td>
<td>c-ii: 1.86E-06</td>
<td>c-iii: 1.86E-05</td>
<td>c-iv: 1.86E-04</td>
<td>c-v: 1.86E-03</td>
</tr>
</tbody>
</table>

Figure 5-26: The impact of IFT on regime transitions with varying injection rates (and Ca), with gravity forces turned off.

Figure 5-27: The impact of IFT on global instantaneous viscous pressure gradient profile for an injection rate of 5.97E-12 m³/s

**5.4.2 Impact of Gravity**

We have just seen why lowering the IFT is generally considered a sound strategy for improving displacement efficiency during enhanced oil recovery. The effect of gravity was, however, not included in the last set of simulations and we now see how its incorporation modifies the earlier results. Figure 5-28 shows that the improvements in displacement efficiency achieved by decreasing the IFT was effectively cancelled out by the effect of gravity. Gravity easily overcame the viscous forces under diminishing capillary forces (even at high injection rates) to force CO₂ to override the in situ brine. It seems that in order to reap the full benefit of lowering the IFT on macroscopic displacement efficiency, it is apparent that very high injection rates would be required.
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5.5 The Impact of Dynamic Viscosity Reduction Due to CO₂ Dissolution on the Displacement Efficiency of Heavy Oil by CO₂

The use of CO₂ as a commercially viable EOR agent has long been recognised, but its widespread adoption has been slow. This is unfortunate since CO₂ EOR also offers, if globally accepted, an alternative means for sequestering CO₂ in order to mitigate global climate change. The physical basis that makes CO₂ a preferred EOR agent over other possible alternatives has been well studied and documented (viscosity, IFT reduction; swelling, density effects, etc) by many researchers (Sohrabi and Emadi, 2012; Jha et al, 2011; Emera and Sarma, 2008; Yang and Gu, 2005; Yang et al, 2005; Bennion and Thomas 1993; Chung et al, 1988; Johnson and Pollin, 1981). We focus here on the impact of heavy oil viscosity reduction due to CO₂ dissolution on displacement efficiency. This is because it is perhaps the most important CO₂-induced oil physical property change which, properly understood, may well decide whether or not CO₂ EOR gets adopted for the extraction of the most abundant reserve of liquid hydrocarbons in the world.

Experiments of various kinds have revealed partial insights into the mechanisms that may be at play during oil displacement by CO₂ but there is hardly any published work that gives an integrated mechanistic account of CO₂ EOR in heavy oil. We have seen that displacement under very adverse viscosity ratios results in extreme viscous fingering, which reduces displacement efficiency even at moderate injection rates. The successful
production of heavy oil via direct displacement by CO₂ would therefore require a front stabilizing mechanism. The restrictive nature of porous media leads us to expect that contact of CO₂ with oil is unlikely to lead to an instantaneous and homogeneous change in oil viscosity even at the ‘zone of contact’. Oil viscosity changes are likely to be gradual and would exhibit non-uniformities dictated by the pore space architecture, the speed of CO₂ advance and the CO₂ dissolution rate. The details by which all these interactions occur have not been rigorously explored and therefore demand urgent attention.

5.5.1 Parameter Selection
The bulk of the heavy oil property data were taken from the laboratory measurements of Bennion and Thomas (1993) and are given in Table 5-1. Other pertinent modelling parameters in Table 5-1 not given in Bennion and Thomas (1993) were estimated from other literature sources. Simulation was carried out at a pressure of 13.169MPa and temperature of 22°C, and all fluid properties are evaluated at this condition and therefore have constant values, except the oil viscosity. Oil viscosity dependence on CO₂ concentration is evaluated using Equation (5-3) which describes the trend line through the experimental data points from Bennion and Thomas (1993).

\[ \mu_o = \begin{cases} \frac{388974}{C^{3.913}}, & C < 28.60744829 \\ \frac{3.0016}{C^{0.412}}, & C \geq 28.60744829 \end{cases} \]  

where, C is the oil CO₂ concentration in kg/m³.

\[ \mu_o \] calculated in Equation (5-3) is then used to determine the effective viscosity in each pore in the network as:

\[ \mu_{eff} = \mu_{g,f} + \mu_o.(1 - f) \]  

where f is the fraction of pore filled with CO₂.

5.5.2 Results and Discussion
Three sets of simulations were performed, each corresponding to a particular assumption about the concentration profile of oil with time. In the first subset of simulations oil was assumed to be CO₂ free and CO₂ dissolution during flow was negligible so that oil viscosity remains constant at the initial maximum value of 25022cP. The second subset assumes a
dynamic evolution of local oil viscosity based on local CO₂ concentration specified by Equation (5-3), whilst the third subset assumes a CO₂-saturated oil with a minimum and constant viscosity of 394cP through the entire injection process.

All results from the three sets of simulations have been displayed on one panel to aid comparison (see Figure 5-29). We can see that a substantial improvement in displacement efficiency was achieved as a result of the real-time reduction in heavy oil viscosity due to CO₂ dissolution (Figure 5-29[b]) compared to the set of simulations with no CO₂ dissolution at all (Figure 5-29[a]). These improvements have been achieved even when the aqueous CO₂ front had moved only a relatively short distance away from the CO₂-oil contact line (Figure 5-29[b-i–ii]). As the injection rate increased and the time available for dissolution per PVI decreased, however, the penetration of the aqueous CO₂ front from the CO₂-oil contact line decreased and so did the displacement efficiency (Figure 5-29[b]). Use of CO₂ as an EOR agent would seem to be effective only at the slow injection rates which guarantee longer residence times.

Further gains in displacement efficiency were achieved by pre-equilibrating the oil with CO₂ in order to decrease its viscosity to the minimum possible value at the simulated conditions before the start of injection (compare Figure 5-29[b] and Figure 5-29[c], and Figure 5-30[a] and Figure 5-30[b]). However, the long equilibration times that will be needed in large scale systems makes this option unattractive in field applications. However, it may be possible to speed up the equilibration process by taking advantage of the geometrical properties of viscous fingers at high injection rates.

By injecting a small volume of sacrificial CO₂ at a high rate into dead oil and then shutting in the well for a pre-determined amount of time, the resulting viscous fingers can help enhance the dissolution process by their deep penetration into the oil bulk and by their relatively large surface contact area with the oil. Even when not all the sacrificial CO₂ dissolves after a protracted shut-in, the oil imbibition processes activated as the free CO₂ goes into solution could lead to the fragmentation of the greater part of the initial viscous fingers, making them hydraulically discontinuous. Thus, when injection is resumed it is unlikely that the new evolution path will coincide with the old path, especially given the altered viscous pressure gradient (and also possibly the capillary pressure distribution,
assuming a change in IFT) profile. The likely bypassing of residual oil that would result from the retracing of the old evolution trajectories can also be suppressed by injecting at a rate lower than that employed for pumping the sacrificial CO₂.

Table 5-1: Details of CO₂ and heavy oil properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Oil viscosity, PaS</td>
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</tr>
<tr>
<td>CO₂ Viscosity (at 13.169 MPa, 22°C; NIST), PaS</td>
<td>8.61E-05</td>
</tr>
<tr>
<td>CO₂-Oil Diffusion Coefficient (at 6.0 MPa, 23.9°C, 23 PaS; Yang and Gu, 2005), m²/sec</td>
<td>5.50E-10</td>
</tr>
<tr>
<td>Initial Oil concentration of CO₂, Kg/m³</td>
<td>11.78</td>
</tr>
<tr>
<td>CO₂-Oil IFT (at 13.169 MPa, 27°C; Yang et al, 2004), mN/m</td>
<td>1.00</td>
</tr>
<tr>
<td>Heavy oil temperature (Bennion and Thomas, 1993), °C</td>
<td>22</td>
</tr>
<tr>
<td>Heavy oil pressure (Bennion and Thomas, 1993), MPa</td>
<td>13.169</td>
</tr>
<tr>
<td>CO₂ density (at STD: 15.56°C, 0.101353MPa; Bennion and Thomas, 1993), kg/m³</td>
<td>1.87</td>
</tr>
</tbody>
</table>

Figure 5-29: The impact of heavy oil viscosity profile due to the aqueous CO₂ concentration on displacement efficiency at varying injection rates: (a) Undersaturated oil with a viscosity of 25022 cP, (b) Partially saturated oil with a concentration-dependent viscosity distribution according to Equation (5-3), (c) Fully saturated oil with a viscosity of 394 cP. The bottom rows in each group (a, b, and c) display both free CO₂ saturation (grey), and aqueous CO₂ concentration (blue=high and white=low).
Figure 5-30: Percentage changes in $S_{gc}$ at different $Ca$ for simulations using (a) oil with a concentration-dependent viscosity function, and (b) a fully saturated oil, over simulations performed using dead oil.

5.6 Comparison of CH$_4$-H$_2$O and CO$_2$-H$_2$O Viscous Regime Transitions

We select two out of the five temperature and pressure conditions at which comparisons of gravity-driven regimes of CH$_4$-H$_2$O and CO$_2$-H$_2$O systems had been made in Chapter Four. The first condition, denoted (TP)$_{crit}$ ($T=35^\circ$C, $P=1500$psia), is meant to simulate conditions near the critical point of CO$_2$. The second, denoted $T_{subP_{super}}$ ($T=25^\circ$C, $P=3500$psia), represents the condition at which the viscosity difference between CH$_4$ and CO$_2$ is at its largest (in comparison to the values at all other temperature and pressure conditions previously considered), Figure 5-31. The condition with the next largest viscosity difference between CH$_4$ and CO$_2$ among the five conditions previously considered is indeed (TP)$_{crit}$. The differences between CH$_4$-H$_2$O and CO$_2$-H$_2$O IFTs are also at their greatest at the two selected conditions among the five temperature and pressure conditions previously considered (Figure 5-31). The networks properties are as described in section 2 of this chapter. Gravity forces are turned off and gas dissolution is disabled. This leaves differences of viscosity ratio and IFT as the possible drivers of differences between flow regimes at any given injection rate.

5.6.1 Results and Discussion

Although the CO$_2$/H$_2$O binary system has a smaller adverse viscosity ratio and a lower IFT compared to the CH$_4$/H$_2$O system at both (TP)$_{crit}$ and $T_{subP_{super}}$, the CO$_2$/H$_2$O binary system also possesses a capillary number that is an order of magnitude higher than for the CH$_4$/H$_2$O system at equivalent injection rates under these conditions (see Figure 5-31). It is therefore not so straightforward to predict a priori from physical properties alone which binary system will exhibit greater displacement efficiency. Figure 5-32 and Figure
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5-33 show that at slow to moderately high rates, similar capillary and viscous fingering patterns were generated for both binary fluid systems at (TP)\text{crit} and T_{sub}P_{super}. This is further confirmed by the virtual overlap of CO\textsubscript{2} and CH\textsubscript{4} S\text{gc} profiles (Figure 5-34) over this range of injection rate – despite the apparently disparate fluid property combinations in both systems the force balance in both systems remained broadly the same. As injection rate was increased beyond a critical value (Q>5.97E-8 m\textsuperscript{3}/s), displacement efficiency in both binary systems increased but at a much higher rate for the CO\textsubscript{2}/H\textsubscript{2}O system than for the CH\textsubscript{4}/H\textsubscript{2}O system (Figures 5-32, 5-33, and 5-34).

The salient implication of these results consists not in the observation that CO\textsubscript{2} displaces H\textsubscript{2}O more efficiently than CH\textsubscript{4} at high injection rates, but that despite the fairly significant disparity between CO\textsubscript{2}/H\textsubscript{2}O and CH\textsubscript{4}/H\textsubscript{2}O properties at the studied temperature and pressure conditions, the displacement behaviours of CO\textsubscript{2} and CH\textsubscript{4} in the range of flow velocity that is probably more characteristic of flow in reservoirs were very similar. In practical terms, this means that once the leading displacement front has moved outside the high flow velocity region around injection wells (or during the post-injection phase of CO\textsubscript{2} sequestration) the approximation of CO\textsubscript{2} flow properties from the flow properties of CH\textsubscript{4} (which might be more readily available) in order to predict the migration pattern of free CO\textsubscript{2} is unlikely to lead to significant errors. The relatively mild effect of dissolution on the migration of free of CO\textsubscript{2} under anticipated temperature and pressure conditions in geological aquifers – as already demonstrated in Chapter Four, should provide additional justification for trusting the validity of such an approximation.

![Figure 5-31: Comparison of CH\textsubscript{4}-H\textsubscript{2}O and CO\textsubscript{2}-H\textsubscript{2}O (a) viscosity ratio, (b) IFT, and (c) CO\textsubscript{2}-H\textsubscript{2}O to CH\textsubscript{4}-H\textsubscript{2}O macroscopic capillary number ratio Ca\textsubscript{CO2-H2O}/Ca\textsubscript{CH4-H2O}, at (TP)\text{crit} (T=35°C, P=1500psia) and T_{sub}P_{super} (T=25°C, P=3500psia)](image)
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Figure 5-32: Comparison of CH$_4$-H$_2$O and CO$_2$-H$_2$O regime transitions with varying injection rates at (TP)$_{crit}$ (T=35°C, P=1500psia).

Figure 5-33: Comparison of CH$_4$-H$_2$O and CO$_2$-H$_2$O regime transitions with varying injection rates at T$_{subP_{super}}$ (T=25°C, P=3500psia).

Figure 5-34: Comparison of CH$_4$-H$_2$O and CO$_2$-H$_2$O S$_{gc}$ profiles as functions of injection rate at (a) (TP)$_{crit}$ (T=35°C, P=1500psia), and (b) T$_{subP_{super}}$ (T=25°C, P=3500psia).
5.7 Nature of Scale-Dependence of Viscous Forces

An often repeated but rarely examined maxim about multiphase flow in porous media is the dependence of viscous forces on scale – as system scale gets larger viscous forces become more dominant. Another way of stating this is that: to maintain the same force balance in two isotropic systems of different dimensions but otherwise identical petrophysical properties e.g. a gridblock and a network model, then the frontal velocity in the smaller system would have to be increased by a factor $N$, where $N$ is the size ratio of the larger system to the smaller system. However, it is not so obvious to deduce from the scaling groups in common use that achieving the same force balance in two systems of different dimensions requires the kind of frontal velocity scaling just described. Take the traditional definition of capillary number given as Equation (5-5),

$$Ca = Q\mu/A\sigma$$  \hspace{1cm} (5-5)

in which $Q$ is the flow rate, $A$ is the cross-sectional area, $\mu$ is the invading phase viscosity, and $\sigma$ the interfacial tension.

If $\mu$ and $\sigma$ in both the large and small systems are assumed the same, then $Ca$ in both systems are matched if the condition,

$$Q_{\text{large}}/A_{\text{large}} = Q_{\text{small}}/A_{\text{small}}$$  \hspace{1cm} (5-6)

or $u_{\text{large}} = u_{\text{small}}$

is satisfied. Thus, all that is required to match the force balance is for the frontal velocity $u$ in both systems to be matched – it is hardly worth noting that this scaling argument requires that $Q_{\text{large}}$ be greater than $Q_{\text{small}}$. The following set of simulations puts this hypothesis to the test.

The simulations were performed with four sets of network dimensions that ranged over an order of magnitude – 38x19x1, spanning a length of 1.14cm; 107x53x1, spanning 3.21cm; 250x124x1, spanning 7.50cm; and 750x370x1, spanning 22.50cm. For each network dimension, five simulations were performed at five pre-selected capillary numbers, $Ca$, as defined by Equation (5-5). Table 5-2 lists the parameters that went into
determining $Ca$ of 1.86E-9 for each network dimension (the corresponding parameter combinations for other $Ca$ values can easily be extrapolated from here).

Figure 5-35 shows that simulations at different scales under the same $Ca$ regime display analogous displacement patterns. And although the response of the displacement pattern to changes in $Ca$ tended to accelerate as simulation scale increased, Figure 5-35 nevertheless suggests that an acceptable scale-up could be achieved by simply matching the apparent frontal velocity (as estimated by the conventional $Ca$ definition) at the reference scale.

A more robust scaling group which takes into account the actual flow equations would be needed to more accurately reproduce the force balance at different scales of interest. Equation (5-7) is an example of such a scaling group as presented in McDougall (1994).

$$Ca^* = \frac{Q\Delta{x}\mu}{\Delta{y}\Delta{z}\sigma\cos\theta \sqrt{k\phi}}$$

Equation (5-7)

For the same average network permeability, porosity and fluid properties, the relevant group to match at different scales reduces to:

$$\frac{Q\Delta{x}}{\Delta{y}\Delta{z}}$$

Equation (5-8)

Table 5-3 compares normalised values of the generalized $Ca^*$ (Equation 5-7) at the four model scales using parameter combinations that correspond to a conventional $Ca$ (Equation 5-5) of 1.86E-9 (also see Table 5-2). It suggests that during scale-up the conventional $Ca$ actually overestimates the frontal velocity needed to reproduce the force balance in the smaller scale system at a larger scale by an amount equal to the factor of the change in scale, hence the differential response of displacement pattern to changes in $Ca$ observed in Figure 5-35. But this was only because the networks are 2D and therefore only two ($\Delta{y}$ and $\Delta{x}$) of the three Cartesian coordinates ($\Delta{y}$, $\Delta{x}$, and $\Delta{z}$) were varied as we moved from one scale to the other. If the networks were 3D and each Cartesian dimension was varied proportionately from one scale to the next, it can be shown that the conventional $Ca$ would underestimate frontal velocity as model scale
increased, and the response of the displacement pattern to changes in $Ca$ would be slowed at larger scales i.e. *in order to reproduce the force balance in the smaller scale at a larger scale the frontal velocity in the larger scale would have to be decreased by a factor $N$, where $N$ is the size ratio of the larger scale to the smaller scale.*

A robust scaling procedure ought to help us identify the key variables that need to be changed and in what direction in order to replicate force balances at different scales. The foregoing has clearly shown how the scaling group conventionally used to scale capillary-viscous force balance falls short of this goal, and also how a naïve interpretation of the more generalised scaling group could easily lead to erroneous outcomes – the possible changes in model aspect ratio due to a change from one scale to the other is just as important a factor to consider as the changes in absolute model dimensions if a consistent force balance is to be maintained at different scales.

**Table 5-2: Network parameters for $Ca$ (Equation (5-5)) of 1.86E-09 at different scales**

<table>
<thead>
<tr>
<th>Porelength, m</th>
<th>3.00E-04</th>
<th>3.00E-04</th>
<th>3.00E-04</th>
<th>3.00E-04</th>
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<td>107</td>
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<td>750</td>
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<tr>
<td>$Ny$</td>
<td>19</td>
<td>53</td>
<td>124</td>
<td>370</td>
</tr>
<tr>
<td>$Nz$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$Q$, m$^3$/sec</td>
<td>1.51E-12</td>
<td>4.22E-12</td>
<td>9.87E-12</td>
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<tr>
<td>$\mu$, PaS</td>
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<td>5.82E-05</td>
<td>5.82E-05</td>
<td>5.82E-05</td>
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<tr>
<td>$\sigma$, N/m</td>
<td>2.76E-02</td>
<td>2.76E-02</td>
<td>2.76E-02</td>
<td>2.76E-02</td>
</tr>
<tr>
<td>$A$, m$^2$</td>
<td>1.71E-06</td>
<td>4.77E-06</td>
<td>1.12E-05</td>
<td>3.33E-05</td>
</tr>
</tbody>
</table>

| $Ca$         | 1.86E-09 | 1.86E-09 | 1.86E-09 | 1.86E-09 |
5.8 Reproducing the Micromodel Displacement Experiments of Lenormand et al (1988)

The 2D micromodel experiments of Lenormand et al (1988) investigating the effect of viscous forces on immiscible displacement behaviour is exemplary by virtue of the wide range of fluid parameters and the displacement configurations studied and the clarity with which the results have been presented. Moreover, the detailed reporting of the
micromodel architecture and the fluid properties facilitates the use of network models for the faithful reproduction of the experimental conditions. We focus here on two subsets of Lenormand et al's displacement experiments – one performed with air displacing oil (A-O; adverse viscosity ratio, $\mu_{\text{air}}/\mu_{\text{oil}}$, of 1.80E-05) and the other involving a viscosified water (glucose solution) displacing a less viscous oil (W-O; favourable viscosity ratio, $\mu_{\text{water}}/\mu_{\text{oil}}$, of 839) – with the goal of reproducing the experimentally observed regime transitions at varying injection rates. By reproducing these experiments it is hoped that the degree of validity of the model of viscous driven flow presented in Chapter Three could be established.

The network model was constructed to match the scale and dimensions (135cmX150cm), the pore size distribution, and the permeability of the 2D micromodel. The resulting 135x150x1 network is made up of 40515 active bonds. The length of a pore in the network model is considered to be equivalent to the average distance between sites in the micromodel (1mm), whilst the equivalent capillary radius of the rectangular cross-sectioned ducts of the micromodel was estimated using the approximation of Lenormand et al (1983) as

$$\frac{1}{r} = \frac{1}{d} + \frac{1}{e}$$

(5-9)

where, $d$ is the depth (constant) of the rectangular ducts of the micromodel, and $e$ the width of a duct which varies from 0.1mm to 0.6mm according to a log-normal distribution function (not given).

The range of network pore radius calculated using Equation (5-9), 91µm – 375µm, was used to randomly assign radii to the bonds in the network using a uniform continuous distribution function. The 2D micromodel was in a horizontal position throughout the experiments and so gravity forces were considered by the authors to be very small. Accordingly, simulations will be run with gravity forces turned off.

Details of fluid properties, operating conditions, and derived values of some relevant scaling groups can be found in Table 5-4. Simulations were initialised at a pressure and
temperature of 14.7 psia and 25°C, respectively, to represent the ambient ‘room temperature’ conditions of the experiment.

Table 5-4: Fluid properties and flow conditions for two sets of immiscible displacement experiments by Lenormand et al (1988).

<table>
<thead>
<tr>
<th>#</th>
<th>A-O</th>
<th>W-O</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>1.8E-05</td>
<td>4.7</td>
</tr>
<tr>
<td>ii</td>
<td>1.8E-05</td>
<td>4.7</td>
</tr>
<tr>
<td>iii</td>
<td>1.8E-05</td>
<td>4.7</td>
</tr>
<tr>
<td>iv</td>
<td>1.8E-05</td>
<td>4.7</td>
</tr>
</tbody>
</table>

5.8.1 Results

Figures 5-36 and 5-37 show that the network model predicts to a high degree of accuracy both the broad trends of the regime transitions with variation in injection rate under adverse and favourable viscosity ratios, and also the displacement patterns in individual model realizations. Even greater predictive accuracy might be achieved if more specific details about the pore size distribution function were available.

![Figure 5-36](image-url)
5.9 Chapter Summary

By coupling the effects of dynamic viscous pressure gradients during a displacement process, analysis of flow behavior was extended to cover flow regimes where the quasi-static assumptions about multiphase flow become inoperative. However, whilst the proper accounting of viscous forces is a necessary condition for describing regime transitions under changing injection rates, the foregoing has shown that the nature of such transitions is strongly context-dependent. The prevailing strength of capillary and gravity forces; the configuration of the defending and the invading phase relative to the orientation of viscous and gravity forces; the viscosity ratio between the defending and invading phases: all these factors exert significant impacts on the nature of the displacement pattern which have first order implications for the characterization of multiphase flow in porous media.

The reduction of IFT is a key process objective during CO$_2$ injection for EOR that is often envisioned to enhance displacement efficiency by reducing the capillary pressure. Simulations involving coupled gravity and viscous effects have, however, shown that the gains in displacement efficiency by lowering capillary pressure are only apparent when gravity is considered negligible. Incorporation of gravity forces in the flow equations caused CO$_2$ to easily override the liquid phase as IFT decreases, leading to a sharp decline in displacement efficiency.
A comparative study of viscous-driven regime transitions of the binary fluid systems of CO$_2$-H$_2$O and CH$_4$-H$_2$O, at two sets of pressure and temperature conditions (T=35°C, P=1500psia; and T=25°C and P=1500psia) shows that despite the fairly significant disparity between CO$_2$/H$_2$O and CH$_4$/H$_2$O properties at these conditions, the displacement behaviours of CO$_2$ and CH$_4$ in the range of flow velocity characteristic of flow in reservoirs were very similar. However, CO$_2$ displacement efficiency began to increase faster than that of CH$_4$ as injection rate was increased beyond a critical point.

We have also seen how the conventional viscous-capillary scaling group fails to meet the essential criteria of replicating force balances at different scales, and also how a naïve interpretation of the more generalised viscous-capillary scaling group could easily lead to erroneous outcomes – the possible changes in model aspect ratio due to a change from one scale to the other is just as important a factor to consider as the changes in absolute model dimensions if a consistent force balance is to be maintained at different scales.

A scoping investigation into the impact of dynamic changes in heavy oil viscosity due to CO$_2$ injection in an EOR process demonstrates how the unique features of the modelling approach adopted here (a realistic treatment of inter-phase mass transfer, efficient handling of the full spectrum of the interactions between capillary, gravity and viscous forces) can facilitate the examination of practical issues in a rigorous way.

Finally, the efficacy of the modelling approach used in this thesis – especially the capillary-viscous coupling – was demonstrated by the reproduction of some immiscible displacement experiments of Lenormand et al (1988), under varying viscosity ratios and capillary numbers. The result displayed excellent agreement between experiment and simulation.