CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The research presented in this thesis is aimed towards an improved understanding of the processes of depressurisation below bubble point pressure and repressurisation, with an emphasis on how they improve recovery from petroleum systems. This has led to the development of a dynamic multiphase network simulator capable of describing the complex process of solution gas drive including the non-equilibrium nature of gas evolution and re-dissolution in oil for disparate porous media. Importantly, the simulator can provide clear insights into both micro-scale and core-scale processes both near wellbore and deep in the reservoir (away from wellbore effects). Extensive parametric studies have been used to systematically investigate depressurisation/repressurisation protocols in a highly efficient and cost-effective manner, something that would not have been possible using only laboratory experiments. While specific details of observations are summarised at the end of each chapter, this chapter summarises the main contributions of this thesis. Furthermore, findings from this research have suggested a number of areas requiring additional investigation and these will be presented at the end.

6.1 Conclusions

6.1.1 Conclusions from depressurisation studies of gas/oil systems

Firstly, conclusions are presented regarding the modelling of depressurisation below bubble point pressure.

*Flow regime transitions during depressurisation:* network simulations have shown that, when maximum Bond numbers are less than unity during depressurisation, growing gas clusters are predominantly capillary controlled and exhibit a more compact topology. This becomes less the case as mean capillary radius increases and/or GOIFT decreases, and the topology becomes increasingly biased vertically (increasing Bond number). As the influence of gravitational forces increases, migratory regimes emerge, ultimately leading to discontinuous, dispersive gas flow. Extensive parametric studies carried out using network
simulations subsequently revealed that four different pore-scale petrophysical parameters primarily affect the transition from non-dispersive to dispersive gas flow during depletion of a gas-oil system. These parameters are:

a. mean capillary radius  
b. network connectivity  
c. interfacial tension  
d. local capillary pressure variance or pore size distribution (PSD) variance

Dispersion is most likely to occur under conditions of large mean capillary radius, small PSD variance, low GOIFT, and high connectivity.

Regime-dependency of final gas saturation: one of the most important findings from this work is that final gas saturation ($S_{gf}$) observed at the end of a depletion varied significantly with flow regime. This was evident in the non-monotonic changes in $S_{gf}$ versus mean capillary radius and GOIFT.

Implication of nucleated bubble density at saturation pressure: investigations of the implications of nucleation density at bubble point on migratory regimes showed that, increasing bubble density did not result in any dramatic changes to the predominant growth regime; however, the relative impact of nucleation density upon recovery was seen to be regime-dependent. Simulation results also suggested that the nucleated bubble density has least effect on final gas saturation when the regime is either capillary controlled or dispersive.

Definition of critical gas saturation: simulations have elaborated the complexities involved with obtaining a generalised definition of critical gas saturation, $S_{gc}$. While $S_{gc}$ defined according to the suggestion of Tsimpanogiannis and Yortsos, (2004) may define $S_{gc}$ as the gas saturation at the onset of mobilisation; simulations have shown that actual gas production depends on both the associated flow regime and experimental protocol (i.e. the relative orientation of gravity and viscous gradients).
Consequences of production boundary designs: accurate modelling of production boundary conditions was found to be important especially when gas migration is discontinuous. Based on simulations considering different production boundary conditions, it was shown that, where all bubbles reaching the outlet buffer are instantaneously produced; final gas saturation (an indicator of oil recovery) may decrease with decreasing interfacial tension within the dispersive regime.

Gas evolution in the presence of three forces and varying network orientations: a wide-ranging study of the effects of gravitational and viscous force orientation and well placement has been presented. Displacement patterns pertinent to both horizontal and vertical wells have been produced and intriguing results derived which serve to highlight a number of important issues associated with each configuration.

For cases where gravity opposes a viscous pressure gradient (as in a network above a horizontal wellbore), for a fixed gravity effect (i.e. inclination angle), increasing the viscous gradient was found to lead to a transition from gravity-stable capillary displacement to a viscous fingering regime. For very large viscous pressure gradients, this eventually led to a largely dispersive pattern of gas flow towards the wellbore. During simulations with small viscous pressure gradients acting in the same direction as gravity (as in a network below a horizontal wellbore), the four previously documented regimes (i.e. continuous capillary, continuous finger, discontinuous channelised and discontinuous dispersive) are still expected. However, gas clusters do not migrate as far in the dispersive regime as is does for large viscous forces. When gravity was orientated perpendicular to viscous pressure gradient (as in a vertical well), a transition from gravity fingering (inducing gas override and delayed gas breakthrough) to viscous fingering (inducing early gas breakthrough of largely continuous gas clusters) to viscous-driven dispersive flow may be expected.

Furthermore, gravity forces acting in a complementary orientation to viscous forces can lead to “incoherent” dispersive flow for a small viscous gradient, while increasing the viscous pressure gradient to larger values for such cases resulted in a transition to a more “coherent” fingering pattern. Such a phenomenon has been reported in Geistlinger et al.,
(2006) and is a further indication that the advanced pore network simulator developed as part of this work is able to capture the wide range of rate dependencies of gas evolution reported in the literature.

Regime surfaces: regime surfaces have been produced for low and high coordination number networks and for pore radii that more closely represent reservoir material. Regime boundaries were found to differ slightly depending on the average network connectivity. These regime surfaces later informed parametization of three-dimensional models for relative permeability studies and demonstrates the value of such plots for model designs which should also be applicable in the laboratory.

Pseudo relative permeability: the concept of regime-dependent pseudo-relative permeability has also been introduced. Three dimensional network simulations parameterised with the aid of the earlier regime surfaces confirmed that regime transition is clearly not a dimensionality effect and so previous conclusions derived from two-dimensional simulations should also prove valid for 3D systems.

Low rate laboratory depletion modelling: the network simulator was used to interpret a low rate depletion experiment which formed a basis for later prediction of repressurisation and secondary depletion. Several scenarios were consequently evaluated to best reproduce the results of the depletion experiment. Results suggested that, bubble nucleation density, diffusion coefficient and outlet boundary condition are crucial to successfully reproducing a depressurisation history.

The design of the end plate used for the actual depletion experiment suggested that the laboratory boundary condition would be more accurately represented by means of “random blocking” of a certain fraction of pores at the production port of the model. Varying the percentage of outlet pores open to gas production yielded a better history-match to the gas saturation and oil production data down to very low pressures. This result demonstrated the importance of boundary conditions in the simulations (and probably the experiment too), especially when dealing with such low depletion/repressurisation rates and small incremental recoveries. Early part of experimental history appeared most sensitive to
diffusion coefficient and improved match was obtained for the early part of the experimental data by refining the values of diffusion coefficient.

Recent improvements in the network anchoring approach (Cf. appendix A) and access to a Linux cluster suggest that the history matching should ideally be repeated in light of these developments. The parameter sets for history matching should therefore not be interpreted as final.

6.1.2 Conclusions emanating from repressurisation studies

As early as the 1920s, repressurisation has been applied as a way of improving oil recovery from conventional oil systems. In the last 5 years, however, experimental investigations using core samples and transparent micromodels have also shown positive results for repressurising heavy oil systems. Crucially, pore level physics relevant during repressurisation were also revealed by these recent experiments. The depressurisation simulator presented in this thesis was also extended to study repressurisation by incorporating experimentally observed pore level physics. This simulator has subsequently been used for extensive parametric studies that form a critical knowledge base for repressurising heavy oil systems. The key contributions are presented below.

*Hysteresis during pressure cycling:* it emerged that knowledge of the position of the dissolved gas concentration in relation to the equilibrium PVT line of the system (i.e. above or below) is essential as the system switches from repressurisation to secondary depletion. Therefore, history of both primary depletion and repressurisation may affect the results of secondary depletion process. The amount of gas remaining at the end of the repressurisation process is a function of the relative rates of primary depletion and repressurisation. Furthermore, snap-off seen during repressurisation was partially reversed once pressure decreased again and this, coupled with the lag in concentration gradients, led to hysteresis in interfacial area between repressurisation and secondary depletion. Consequently, mass transport of gas into the bubbles also exhibited hysteresis. Hysteresis in gas saturation observed during repressurisation is essentially a manifestation of hysteresis in more
fundamental properties including, supersaturation, interfacial area, total number of gas clusters, and the total mass in the gas phase. Reimbibition occurring during repressurisation (which is not a reverse of drainage as modelled here) acts to fragment the gas structure, leading to an increase in the number of gas clusters. Although the number of gas clusters may increase during repressurisation, the discrete nature of these fragmented clusters dramatically reduce the diffusive efficacy into oil.

Repressurisation pressure & secondary recovery: the merits of repressurisation followed by secondary depletion depend upon the abandonment pressure of the system in question. However, the degree of additional recovery seems to depend nonlinearly upon the pressure at which repressurisation is begun.

Average coordination number impact on secondary recovery: although oil production was lower overall in the less connected system, the increase in production of OOIP through performing a repressurisation-secondary depletion cycle was considerably larger. Studies presented here suggest that reduced network connectivity promotes incremental recovery from secondary depletion.

Implication of pore size distribution (PSD) variance on pressure cycle: it appears that increasing the variance of the pore size distribution plays a similar role to that of reduced connectivity. The fragmentation of gas is delayed and the total number of daughter bubbles remaining at the end of repressurisation reduces when PSD variance is increased.

Pressure cycling vs. shut-in: simulation results do suggest that shutting in without repressurising would appear to give optimal recovery compared to pressure cycle. Moreover, the temporal evolution of gas build up demonstrated that the shut-in protocol increased recovery more quickly than if the pressure cycle was used.

Effect of intermittent shut-ins on network gas saturation: in summary, results seem to indicate that shut-in may result in an apparent increase in recovery during an interrupted core depressurisation experiment due to the supersaturated system gradually returning
towards equilibrium over a period of constant average pressure. However, the shut-in does not appear to significantly affect the ultimate recovery if the depletion is resumed down to very low pressures.

*Localised effect of concentration gradient on repressurisation:* local depressurisation effects are seen to occur (i.e., gradients in $R_s$ towards bubbles are still apparent) in some areas of the system during the early stages of repressurisation — time is required for diffusion to reverse these gradients in oil-filled regions far from the gas phase. This effect is exaggerated when the ratio of depletion to repressurisation rates $\gg 1.0$.

*Implications of predominant nucleation process:* instantaneous nucleation simulations showed increases in recovery of up to 5% depending upon the number of bubbles nucleated during primary depletion. This was shown to be directly related to the hysteresis in the number of gas clusters over the pressure cycle. For a fixed rate of DPI-RP-DPII, calculated additional recovery remained positive over a wider pressure range for the higher rate protocol experiment. Additional recovery was seen to consistently increase with decreasing diffusion coefficient under conditions of instantaneous nucleation.

For progressive nucleation, the *onset* of nucleation was insensitive to diffusion coefficient (for systems with the same critical supersaturation), whilst the total number of nucleated bubbles was affected (via local supersaturation). Average supersaturation declined faster in the system with the larger diffusion coefficient, ultimately resulting in the nucleation of fewer bubbles. Hence, the situation is rather more complex than that resulting from instantaneous nucleation. It appears that there may be an optimum diffusion coefficient that maximises additional recovery when progressive nucleation is the dominant nucleation mechanism. This is due to the fact that diffusion not only affects gas growth in this case but also bubble density during primary depletion. Increasing the cavity size not only reduced critical supersaturation but also caused more bubbles to be nucleated as the depletion proceeded. A clear consequence of early activation of cavities is that supersaturation starts falling relatively early and, for the same number of activated cavities, solution gas drive is less effective when critical supersaturation is lower. Diffusion coefficient significantly
affects both the nucleation process and the growth of gas bubbles. In comparison to earlier 2D work, diffusion seemed to have a larger impact on recovery hysteresis in three dimensions.

*Pressure for onset of secondary depletion:* it appears that the degree of additional recovery depends nonlinearly on the pressure at with DPII is started — repressurise too little and the gas phase is poorly fragmented prior to secondary depletion: repressurise too much and the fragmented bubbles begin to go back into solution. This is fully consistent with earlier observation from two dimensional simulations.

*Influence of mean capillary radius:* growth of gas is enhanced with an increase in the mean pore size. Consequently, the model quickly approaches equilibrium when the mean pore size is larger. Supersaturation is therefore higher with a *reduction* in mean pore size, resulting in better additional recovery following a repressurisation phase.

*Implications of repressurisation rate for gas fragmentation and secondary recovery:* it was observed in both 2D and 3D models that a high repressurisation rate leaves many more daughter bubbles within the system prior to secondary depletion in comparison with low rate repressurisation. As a consequence of this, observation from simulations also shows that for equal DPI and DPII rates, secondary recovery generally increased with an increase in repressurisation rate.

*Low rate laboratory repressurisation modelling:* repressurisation simulations using depletion history-matched model did not show any unexpected increase in gas saturation and oil production curves during the secondary depletion. A full primary depletion was also carried out for comparative purposes. Using the same combination of diffusion coefficient, boundary condition, and cavity density, it was shown that low rate repressurisation would not be expected to give additional recovery over that possible via a full depletion.
6.2 Additional applications of research finding

Developments during this research have primarily focused on recovery from gas-oil systems undergoing depressurisation and repressurisation. However, the simulator and the findings from this research clearly have applications in other areas that are currently of active interest by the research community and industry such as:

- **CO$_2$ sequestration**- investigation of CO$_2$ migration and trapping mechanisms during injection in subsurface reservoirs.
- **Contaminated ground water remediation**- study of gas flow regimes and implications for optimising gas injection to volatilise ground water organic contaminants.
- **Steam-assisted gravity drainage (SAGD)**- understanding steam chamber development patterns during SAGD and its derivatives.

6.3 Recommendations for future investigations

It is highly encouraging that simulation results presented in this thesis are consistent with a range of experimental phenomena reported in the literature. Future work should focus on the following important aspects of the study:

(i) Experiments in the literature have shown that viscosity significantly affects the rate of migration of gas bubbles. Therefore, some additional research is needed to accurately evaluate the impact of oil viscosity on flow transitions using some model systems (e.g. tubes) under both simulation and laboratory environments.

(ii) The network model needs additional calibration with experimental parameters for quantitative prediction of recovery, saturation profiles, relative permeability and other relevant parameters *at the correct scale*. For example, the Dumoré work should be repeated at the experimental length scale — simulations can now be run at a size that is appropriate to the experiment of interest and should therefore be used as such in future. Additional comparisons against available experimental data should also be sought.
(iii) The full envelope of regime-dependent steady- and unsteady-state relative permeabilities should be produced to facilitate development of the necessary weighting functions. A start has been made on this aspect of the problem and some preliminary results have been presented but additional work is required.