Flow Visualization and Simulation of Miscible Displacement with Gravity Domination

A thesis Submitted for

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Petroleum Engineering

By

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Abstract

Gravity assisted miscible gas injection into oil reservoirs is an efficient method of Enhanced Oil Recovery (EOR). Carbon dioxide injection into aquifers for sequestration purposes is another application of miscible displacement under gravity control. This dissertation reports pore-scale experimental and simulation studies to determine the role of different parameters on the frontal stability of the miscible displacement process under gravity domination.

Experimental studies were based on visualization of first contact miscible flooding under gravity domination. Visualization was conducted using the glass micromodel technique. Facilities were designed and fabricated to perform the experiments. Two micromodels with different patterns of loose packing and close packing were prepared through the sandblasting technique. The porous patterns for these micromodels were generated using the MATLAB program. The injection of the lighter and less viscous iso-octane was carried out in comparatively heavier and high viscous butanol. The injections were carried out at different dipping angles ($0 \leq \theta \leq 90$) and injection velocities (representing near wellbore and reservoir flow rates). The images were captured and processed to analyse the frontal movement and to estimate the concentration of injecting fluid in the flow domain. The experimental results presented in this thesis demonstrate the dependencies of various characteristics such as dip angle and porous medium heterogeneity on the process at pore scale.

The simulation studies were performed using the Finite Element Analysis technique. The simulation model was initially validated by matching results with flow visualization experimental studies using glass micromodels. The Navier–Stokes, continuity and convection-diffusion equations were used in the simulation instead of Darcy's law. Wide ranges of parameters applicable for Enhanced Oil Recovery and CO_2 sequestration were used in the sensitivity study. Dip angles (θ) between 0^o and 180^o (for up-dip and down-dip situations), different domain velocities, density differences of 50 to 900 kg/m^3 between the injecting and displaced fluids and viscosity ratios from 1 to 100 (to include light and heavy oils) were investigated. Snapshots were captured in each simulation case for visual comparison of the frontal advancement. In addition, breakthrough saturation was plotted against cos (θ) to quantify the competition

between viscous and gravity forces in the gravity-dominated miscible displacement process.

The pore-scale study suggests that the stability of a miscible process can be influenced by several factors. When gravity acts in favour of displacement and there is a moderate to large density difference, angular tilt is the most important parameter influencing displacement. When the density difference is small, then the mobility ratio and flow velocity also play a role. When gravity opposes displacement and buoyancy forces are dominating, results show little sensitivity to the actual tilt angle. Better displacement is seen for lower density difference and for higher flow velocity; yet, again, the mobility ratio only impacts on displacement when the density difference is quite small.

The sensitivity simulation studies were performed based on: (a) mobility ratio, density difference and angle of tilt; (b) domain velocities; and (c) local and global heterogeneity. The sensitivity study for $0 \leq \theta \leq 90$ suggests a region that is sensitive to angular dip. The region $90 < \theta \leq 180$, however, is more sensitive to the density difference between injection and inplace fluids. For $0 \leq \theta \leq 180$ mobility ratio might be significant if the density difference between injection and inplace fluid is small. Sensitivity based on domain velocity suggests that large reduction in domain velocities might lose the inertial effects and might cause overriding, especially for the high-dipping angle cases. Sensitivity based on heterogeneity suggests that decreasing grain spacing promotes the fluid mixing. Therefore, in less permeable zones, the overriding of lighter fluid can be reduced even in high-dipping angle cases.

Statement of Originality

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List of Publications

Zeeshan Mohiuddin, Manouchehr Haghighi and Yvonne Stokes (2013). 'Pore level visualisation and simulation of CO_2 miscible injection with gravity domination', Energy Procedia, **37:** 6885–6900.

Zeeshan Mohiuddin, Manouchehr Haghighi and Yvonne Stokes. 'Pore level visualisation and simulation of CO_2 miscible injection with gravity domination', paper presented at the 11th International Conference on Greenhouse Gas Control Technologies, Kyoto International Conference Centre, Japan, 18–22 November 2012.

Zeeshan Mohiuddin, Manouchehr Haghighi, Yvonne Stokes, Themis Carageorgos and Danny Gibbins. 'Pore scale visualization and simulation of miscible displacement process under gravity domination', paper IPTC 15310 presented at the International Petroleum Technology Conference Bangkok, Thailand, 15–17 November 2011.

Zeeshan Mohiuddin and Manouchehr Haghighi. 'Visualization of CO_2 displacement process under gravity domination", paper SPE 144101 presented at the SPE Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia, 19–21 July 2011.

Abbreviations, Prefixes and Symbols

Breakthrough Saturation (S_b)

Carbon Capture and Storage (CCS)

Cyclic Gas Injection (CGI)

Density Difference ($\Delta\rho$)

Diffusion Coefficient (D_o)

Enhanced Oil Recovery (EOR)

First Contact Miscibility (FCM)

Gas Assisted Gravity Drainage (GAGD)

Hue Saturation and Value (HSV)

Original Oil in Place (OOIP)

Minimum Miscibility Pressure (MMP)

Mobility Ratio (M)

Multiple Contact Miscibility (MCM)

Red Green Blue (RGB)

Water Alternating Gas (WAG)