Evaluation of Empirical Models for Viscous Fingering in Miscible Displacement

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Motivation

The performance of miscible gas injection projects can be significantly affected by viscous fingering. This is further complicated by the presence of heterogeneities, as depending on the scale of the heterogeneity, there can be a diffusive, advective or channelling effect. To assess the economic feasibility of a miscible gas injection project, reservoir simulations are needed but very fine grids are required for the fingers to be modelled explicitly. This requires a large amount of computational power and time. To get around this issue, many empirical models have been proposed which model the average behaviour of the viscous fingers, allowing predictions of performance, thus reducing grid size and computational time. Many previous studies have investigated the ability of empirical models to represent fingering in line drives but none have considered flow in a quarter five spot pattern

Overview of Empirical Models

Todd & Longstaff Model

Fractional flow equation:

$$f_s = \frac{C}{C + \frac{(1-C)}{M_e}}$$

where

$$M_e = \left(\frac{\mu_o}{\mu_s}\right)^{1-\omega}$$

To account for the effect of heterogeneities, ω can be adjusted to match the Koval model which includes a heterogeneity factor, H_k

$$\omega^* = \omega - \frac{\log H_k}{\log \frac{\mu_o}{\mu_s}}$$

where ω is the normal choice of ω (e.g. $\omega = {}^{2}/_{3}$)

Characteristic velocity of the solvent:

$$\frac{df_s}{dC} = \frac{M_e}{(C(M_e-1)+1)^2}$$

Fayers Models:

Fractional flow equation:

$$f_f = \frac{\Lambda\mu_o}{(1-\Lambda)\mu_f + \Lambda\mu_o}$$

where

$$\Lambda = a + bC_f^{\alpha} \quad \& \quad \mu_f = \left(\frac{C_f}{\mu_s^{1/4}} + \frac{1-C_f}{\mu_o^{1/4}}\right)^{-4}$$

Characteristic velocity of the solvent:

$$\frac{df_s}{dC} = \frac{\Lambda\mu_o}{D^2[\Lambda + C_f\Lambda']}\left\{D + C_f\left[\frac{\Lambda'}{\Lambda}\mu_f - \mu_f'(1-\Lambda)\right]\right\}$$

where

$$D = (1-\Lambda)\mu_f + \Lambda\mu_o \qquad \Lambda' = \alpha bC_f^{\alpha-1} \quad \mu_f' = -4\mu_f^{5/4}\left(\frac{1}{\mu_s^{1/4}} - \frac{1}{\mu_o^{1/4}}\right)$$

Modified Fayers Models:

Variable growth rate of fingers:

$$\alpha = cC_f^d + e$$

where

$$c = H_k^2(2.23\ln M - 3.35) \quad d = 9.3 - 280M^{-1.85} \quad e = 0.48H_kM^{0.4}$$

Characteristic velocity of the solvent:

$$\frac{df_s}{dC} = \frac{\Lambda\mu_o}{D^2[\Lambda + C_f\Lambda']}\left\{D + C_f\left[\frac{\Lambda'}{\Lambda}\mu_f - \mu_f'(1-\Lambda)\right]\right\}$$

where the modified Λ' is

$$\Lambda' = bC_f^{\alpha}\left(\frac{\alpha}{C_f} + cdC_f^{\alpha}\ln C_f\right)$$

Methodology

A two phase, three component higher-order simulator is used to simulate miscible injection in square line drive and quarter five spot models, with and without heterogeneities. The results of the detailed fingering simulations were compared to the Todd & Longstaff and Fayers empirical models. To account for the effect of heterogeneities, the mixing parameter, w, in the Todd & Longstaff model was adjusted using Koval's heterogeneity factor, H_k. The growth rate of the fingers, α, and the final fraction of the cross section occupied by the fingers, $a + b$, were adjusted in the Fayers model to account for heterogeneities and bypassed oil. The empirical models were implemented in a commercial immiscible reservoir simulator, ECLIPSE-100 using pseudo relative permeabilities

MISTRESS Simulations

- A FORTAN based software was used to explicitly model viscous fingering in line drive and quarter five spot patterns at various viscosity ratios. The Koval heterogeneity factor was also calculated for all models

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Analytical Solution

- MATLAB® was used to obtain an effluent profile for a 1D line drive from the empirical models using a Buckley-Leverett solution and compared to the MISTRESS simulations

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ECLIPSE Simulations

- The three empirical models were implemented in ECLIPSE-100, a industry standard immiscible simulator to allow for testing in realistic reservoir geometries in 2D and 3D and the results were compared to the MISTRESS simulation

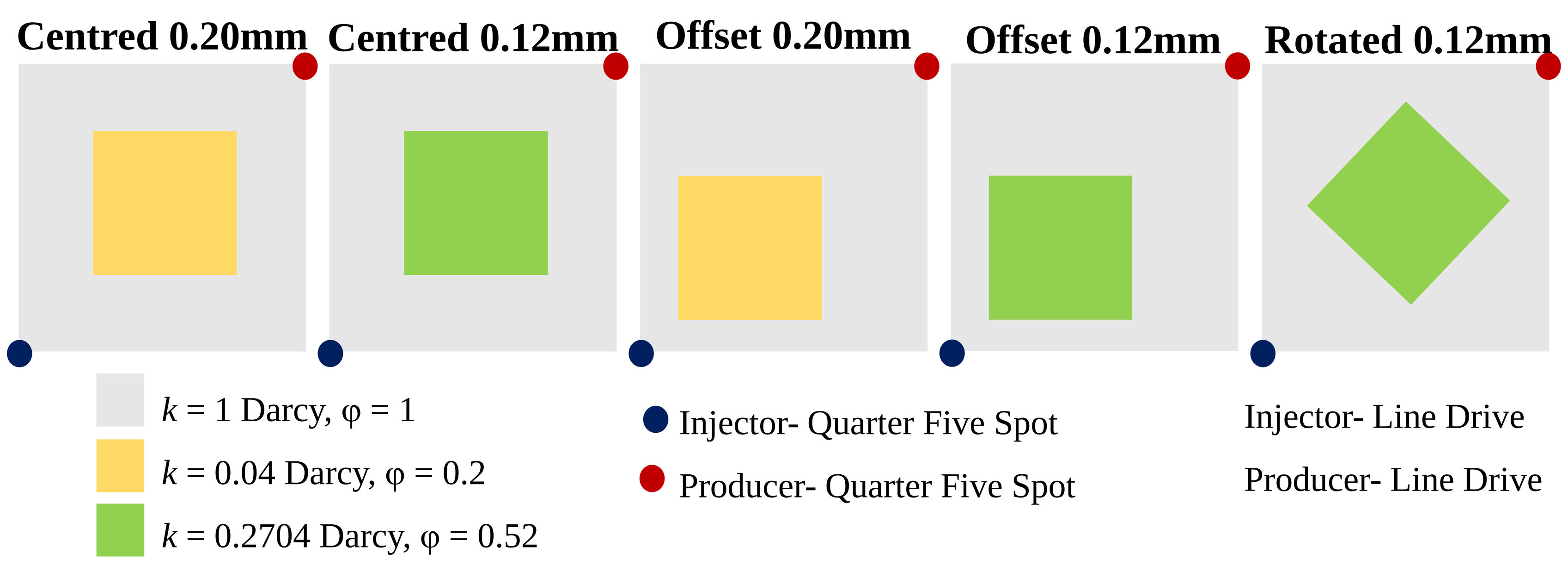

Figure 1- Schematic of the various heterogeneities used in this study

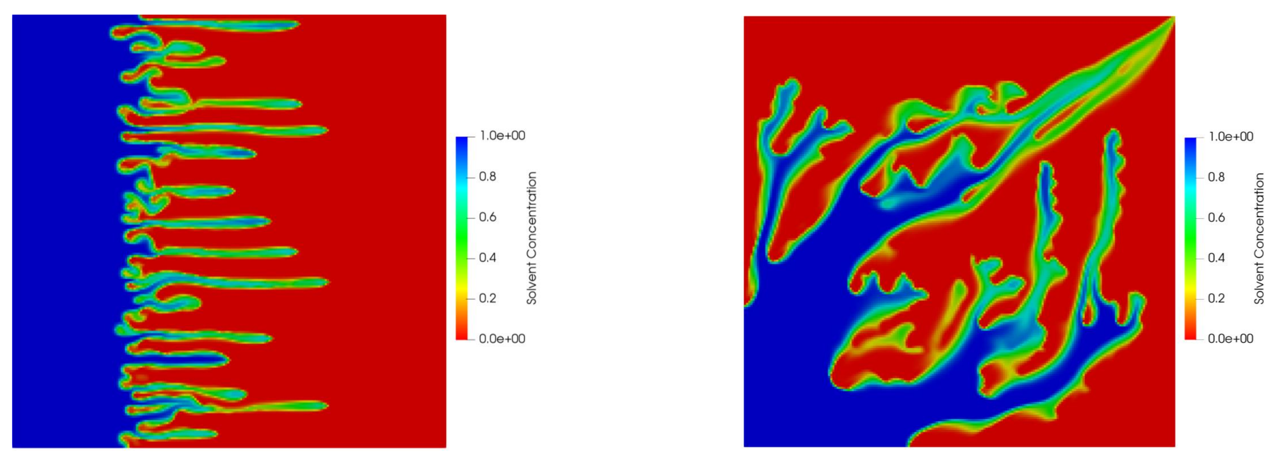

Figure 2- Examples of viscous fingering in a line drive (left) and quarter five spot (right)

Results

Line Drive

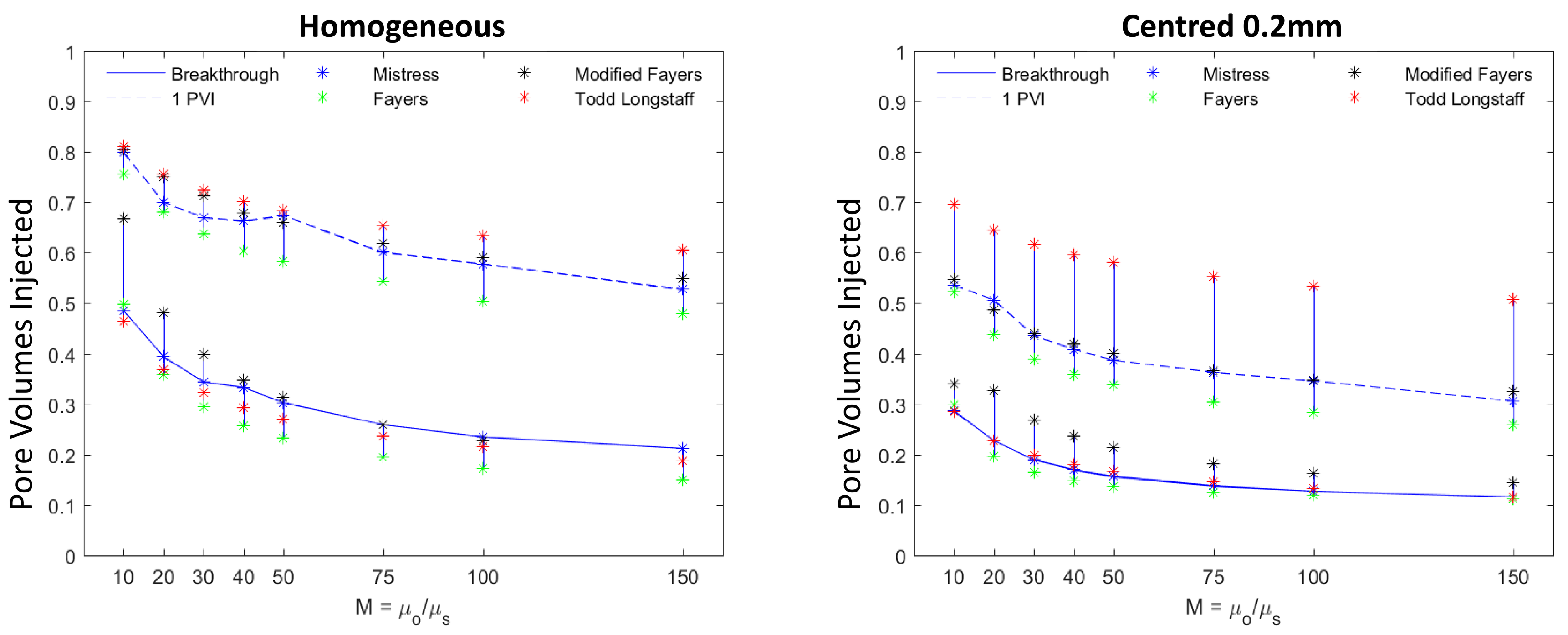

Figure 3- Oil recovery at solvent breakthrough and at 1 PVI for various mobility ratios in a homogeneous and heterogeneous line drive

Quarter Five Spot

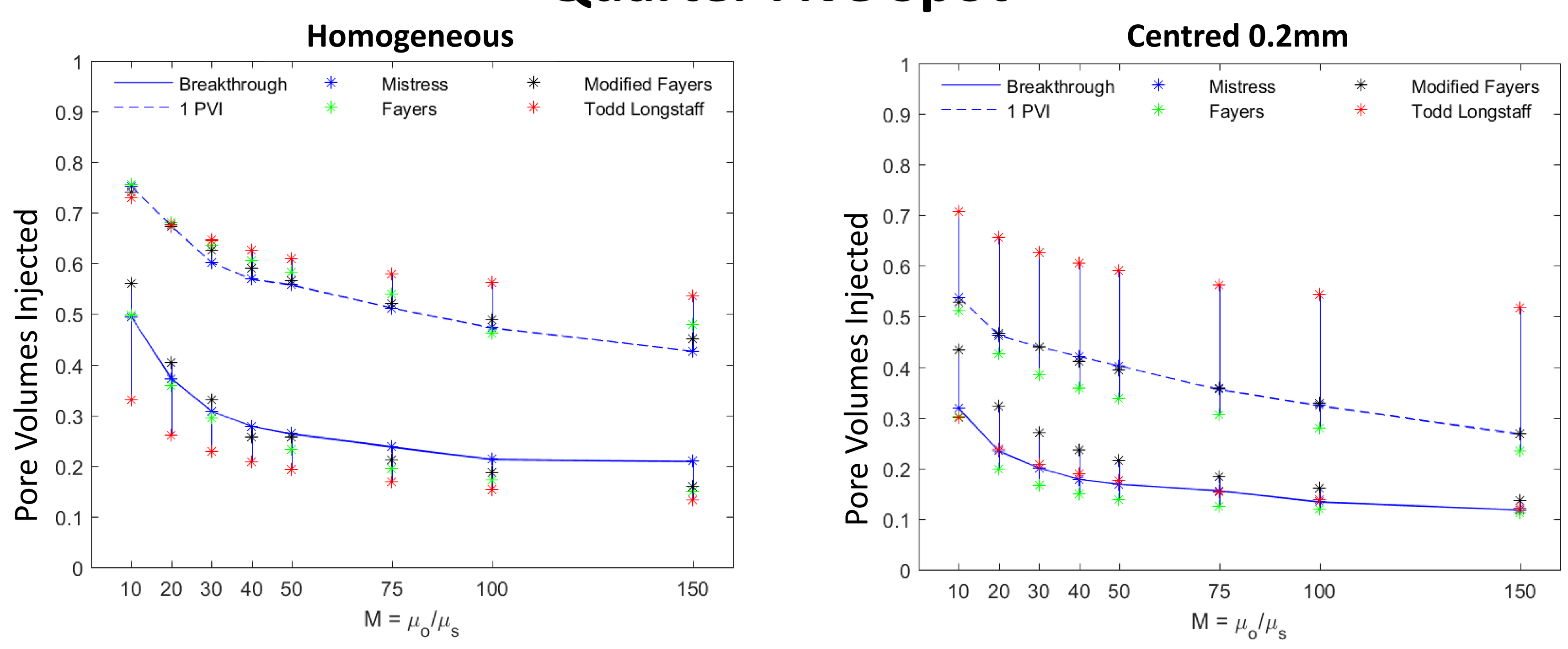

Figure 4- Oil recovery at solvent breakthrough and at 1 PVI for various mobility ratios in a homogeneous and heterogeneous line quarter five spot

Conclusions

The detailed simulations indicate that the growth rate of the fingers varies non-linearly with mean concentration in radial flows and this is not captured by either of the empirical models. A modification of the Fayers model is proposed to capture this. For both heterogeneous line drive and quarter five spot models, the Todd & Longstaff model consistently overestimates recovery after solvent breakthrough as it cannot account for bypassed oil. The Fayers model underestimates recovery whereas the modified Fayers model tends to overestimate the breakthrough time, but after this point, it can accurately reproduce the effluent profile from simulations. However, this requires production data or detailed fingering simulation data to calibrate b, the constant which defines bypassed oil, as this depends on the heterogeneity, the mobility ratio and the time scale of interest