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The effect of displacement rate on imbibition relative permeability and residual saturation

Viet Hoai Nguyen [a], Adrian P. Sheppard [b], Mark A. Knackstedt [b], W. Val Pinczewski [a,*]

[a] School of Petroleum Engineering, University of New South Wales, Sydney, Australia
[b] Department of Applied Mathematics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, Australia

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Abstract

A dynamic network model for imbibition based on a physically realistic description of the complex dynamics of film flow, film swelling and snap-off is described. The model shows that film swelling is a capillary driven nonlinear diffusive process and that the competition between snap-off and frontal displacements is rate dependent resulting in rate dependent relative permeability curves and residual saturations. In contrast to existing quasi-static network models where snap-off is suppressed by contact angle alone, the dynamic model introduces displacement rate as an additional snap-off inhibiting mechanism. The network model is used to analyse the complex interaction between displacement rate, contact angle, aspect ratio and pore and throat shapes on relative permeability. Computed relative permeabilities and residual saturations are compared with laboratory measured data for strongly water-wet Berea sandstone. It is concluded that the magnitude of the rate effect on relative permeability for a particular rock and wetting state depends largely on the aspect ratio. Higher aspect ratios produce larger rate effects than smaller aspect ratios.

Keywords: Network model; Porous media; Berea; Aspect ratio; Imbibition; Relative permeability; Snap off; Capillary number; Dynamic; Films

1. Introduction

Relative permeability and residual saturation are critical parameters in the evaluation of the recovery performance of petroleum reservoirs. Laboratory tests to measure these parameters are often carried out at high rates to minimise capillary end effects (Rapoport and Leas, 1953). The rates are significantly higher than typical reservoir displacement rates and in applying the measurements to reservoir conditions it is assumed that relative permeability and residual saturation are independent of displacement rate (Odeh and Dotson, 1985).

The assumption that relative permeability is independent of rate may be valid for drainage displacements (Akin and Demiral, 1997; Virnovsky et al., 1998) but it is not clear if this is true for imbibition displacements. Labastie et al. (1980), Chen and Wood (2001), Odeh and Dotson (1985) and Qadeer et al. (1988) report that laboratory imbibition water–oil relative permeabilities are independent of rate after accounting for capillary end effects. On the other hand, Heaviside et al. (1987), Kamath et al. (1995), Mohanty and Miller (1991), Ringrose et al. (1996), Skauge et al. (2001) and Wang and Buckley (1999) conclude that displacement rate is important. To confuse matters further, Fulcher et al. (1985) conclude that relative permeability depends on capillary number but that the effect of displacement rate

* Corresponding author.
E-mail address: v.pinczewski@unsw.edu.au (W. Val Pinczewski).

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is unimportant. Most of the measurements reported in these studies are for sandstone cores and cover a wide range of wetting conditions.

A similar lack of consensus appears to exist in the network modeling literature. Blunt (1997), Constantinides and Payatakes (2000), Hughes and Blunt (2000) and Mogensen and Stenby (1998), amongst others, describe numerical network models in which flow in wetting films and the subsequent snap-off of non-wetting fluid ahead of the displacement front result in rate dependent imbibition relative permeabilities. The network models are based on pore-scale displacement mechanisms observed in transparent micromodel experiments (e.g., Lenormand et al., 1983; Vizika et al., 1994) and show that rate effects remain important down to very low displacement rates—capillary numbers $Ca = 10^{-6}$–10^{-8} where the capillary number is the viscous to capillary force ratio written as,

$$Ca = \frac{\mu v}{\sigma} \quad (1)$$

μ is viscosity, v is the displacement velocity and σ is the interfacial tension. In contrast, elaborate three-dimensional quasi-static network models, based on realistic representations of actual sandstone morphology, which ignore rate effects have been successfully used to predict laboratory measured imbibition relative permeabilities (e.g., Blunt et al., 2002; McDougal et al., 2001; Øren et al., 1998; Øren and Bakke, 2003; Patzek, 2001; Valvatne and Blunt, 2003).

The effect of displacement rate on residual saturation is less controversial. Chatzis and Morrow (1984) showed that waterflood residual oil saturation for a wide range of water-wet consolidated sandstones decreases with increasing capillary number. The reductions in residual saturation occurred at significantly smaller capillary numbers than those required for mobilisation of discontinuous oil. Maldal et al. (1997) report similar results for reservoir cores from a number of North Sea fields displaying a range of wettabilities. Residual saturations for carbonate rocks appear to display a greater sensitivity to flooding rate. Kamath et al. (1995, 2001) showed that corefloods on cleaned and restored state heterogeneous carbonate cores displayed large reductions in residual oil saturations with increase in capillary numbers from 2×10^{-8} to 4×10^{-7}. The reductions could not be attributed to capillary end effects. In a recent study Tie and Morrow (2005) report the results of a rate sensitivity study for three outcrop limestones—homogeneous and heterogeneous grainstones and a high porosity/permeability boundstone. Waterflood residual saturations for all three limestones displayed a sensitivity to flooding rate at capillary numbers much lower than measured for the mobilisation of oil both for strongly water wet and mixed wettability conditions.

Snap-off of non-wetting fluid ahead of the displacement front is an important trapping mechanism in imbibition displacements (Chatzis et al., 1983; Chatzis and Morrow, 1984; Kamath et al., 2001; Lenormand and Zarcone, 1984; Mohanty et al., 1980) and the competition between snap-off and frontal displacements determines the pattern of the displacement and therefore the shape of the relative permeability curves and the value of residual saturation (Hughes and Blunt, 2000). Dynamic effects resulting from flow through wetting films can affect the competition between snap-off and frontal displacements and a number of dynamic network models have been proposed to account for this (Blunt and Scher, 1995; Constantinides and Payatakes, 2000; Mogensen and Stenby, 1998; Hughes and Blunt, 2000, 2001). All of the models are based on simplified treatments of flow through films—constant film conductivities, steady-state flow and ad hoc applications of the snap-off mechanism. None of these models capture the complex dynamics of film flow, swelling, snap-off and slow cluster growth by pore filling ahead of the displacement front. Moreover, no attempt was made to compare model predictions with measured relative permeability and residual saturation data.

We present a new network model for imbibition displacements which captures the complex dynamics of film flow and the rate-dependent competition between snap-off and frontal displacements. The model displays all the important pore-scale physics observed in micromodel displacement studies—time-dependent swelling of wetting films ahead of the displacement front, local fluctuations in film pressure and thickness, slow filling of snap-off sites ahead of the displacement front, snap-off initiated cluster growth and the suppression of snap-off with increasing displacement rate. The only assumption made is that viscous gradients in bulk fluid (fluid occupying the centres of pores and throats) are negligible. This is a reasonable assumption for capillary numbers $Ca = 10^{-4}$–10^{-3} (Dullien, 1992).

We use the model to investigate the complex interaction between displacement rate, contact angle, pore–throat aspect ratio and pore and throat shapes on relative permeability and residual saturation and attempt to resolve apparent contradictions regarding the effect of displacement rate on laboratory measured data. We compare predicted relative permeabilities with measurements reported by Oak (1990) for strongly water-wet Berea sandstone. This data has previously been used to