THE EFFECTS OF DISPLACEMENT RATE AND WETTABILITY ON IMBIBITION RELATIVE PERMEABILITIES

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ABSTRACT

A new dynamic network model is used to investigate the effects of displacement rate and wettability on imbibition relative permeability. The network geometry and topology is representative of Berea sandstone. In contrast to existing quasi-static network models where snap-off, the major pore-scale trapping mechanism in imbibition, 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 rate dependence of relative permeability and residual saturation displayed by laboratory measured data reported in the literature.

INTRODUCTION

Relative permeability is a critical parameter for evaluation of reservoir performance and is usually considered to be unaffected by displacement rate. Laboratory measurements are often carried out at high rates to minimise capillary end effects. The rates are significantly higher than typical reservoir displacement rates. The assumption that relative permeability is independent of rate may be valid for drainage displacements [1,2] but it is not clear if this is true for imbibition displacements. Labastie *et al*. [3], Odeh and Dotson [4], Qadeer *et al*. [5], and Chen and Wood [6] report that laboratory imbibition water-oil relative permeabilities are independent of rate after accounting for capillary end effects. On the other hand, Fulcher *et al*. [7], Heaviside *et al*. [8], Mohanty and Miller [9] Kamath *et al*. [10], Ringrose *et al*. [11], Wang and Buckley [12] and Skauge *et al*. [13] conclude that displacement rate is important. Most of the measurements reported in these studies are for Berea or other sandstone cores for strongly water-wet to intermediate wet conditions.

A similar lack of consensus appears to exist in the network modeling literature. Blunt [14], Mogensen and Stenby [15], Hughes and Blunt [16] and Constantinides and Payatakes [17], amongst others, describe numerical network models in which flow in wetting films and the subsequent snap-off of the 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 micro-model experiments [e.g.,18,19] and show that rate effects remain important down to very low displacement rates (capillary numbers, $Ca=10^{-8}–10^{-6}$). In contrast, elaborate three-dimensional quasi-static network models, based on realistic representations of actual sandstone morphology, that ignore rate effects have been successfully used to predict laboratory measured imbibition relative permeabilities [e.g., 20-25].

Nguyen *et al*. [26] have recently described a dynamic network model for film flow and snap-off for imbibition displacements. 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 $Ca=10^{-4}–10^{-3}$ [27]. The model differs from previous models in that it makes no *ad-hoc* assumptions regarding the conductivity of films or the nature of film flow and provides a physically realistic and mathematically rigorous treatment of the complex transient dynamics of film flow, film swelling and snap-off. The model shows that snap-off ahead of the displacement front is suppressed by increasing displacement rate. The effect is qualitatively similar to the effect of contact angle (wettability) in quasi-static models.

We use the model to investigate the complex interaction between displacement rate, contact angle, pore and throat size distributions (aspect ratio), and pore and throat shapes on relative permeability and compare predicted relative permeabilities with measurements reported by Oak [28] for strongly water-wet Berea sandstone. This allows us to resolve a number of apparent contradictions in the laboratory measurements and modeling approaches discussed above. We conclude that the magnitude of the rate effect on imbibition relative permeability, for a particular wetting state, depends largely on the pore-throat aspect ratio. For cores with high aspect ratios (large pores and small throats) the rate effect is large. For low aspect ratios (pores and throats of similar size) the rate effect is small. The implications for laboratory relative permeability testing are obvious.

Network Model for Imbibition

Full details of the dynamic network model are given in Nguyen *et al*. [26]. Here we summarise only those aspects necessary to understand how the model is applied to the study of rate effects. The porous medium is represented by a topologically equivalent network of pores and interconnecting throats for Berea sandstone. The equivalent network was derived by Oren *et al.* [20] and Oren and Bakke [21], and a modified form of the network was used by Blunt *et al*. [24] and Valvatne *et al*. [25] to match the imbibition relative permeability curves measured by Oak [28] for strongly water-wet Berea sandstone. We use the modified network in the present computations. The network contains approximately 12,000 pores and 26,000 throats and represents a cube of rock having a volume of approximately 27 mm^3 (~20 grains a side). Pore and throat size distributions are shown in Fig.1(a).

Pores and throats are assumed to have regular polygonal cross-sections. Although Oren *et al*. [20] and Oren and Bakke [21] approximate actual pore and throat shapes by irregular triangles, we choose to use regular polygons in order to more clearly show the effect of pore shape on the computed relative permeability curves. The polygonal geometry is an essential because it allows macroscopic (thick) films of wetting films stabilized by capillary pressure to form in the corners of pores and throats occupied by non-wetting fluid. These films allow wetting fluid to displace non-wetting fluid ahead of the displacement front. Fig.2 shows the distribution of water wetting films in a triangular capillary for decreasing capillary pressures.

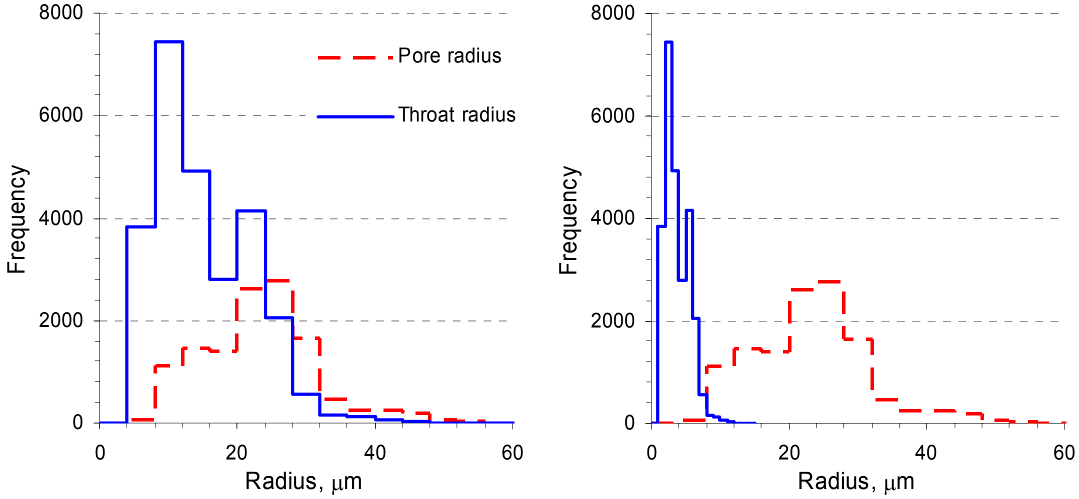

Fig.1 – (a) Measured pore and throat sizes for Berea sandstone [21]. (b) Modified pore and throat size distributions to increase pore-throat aspect ratio.

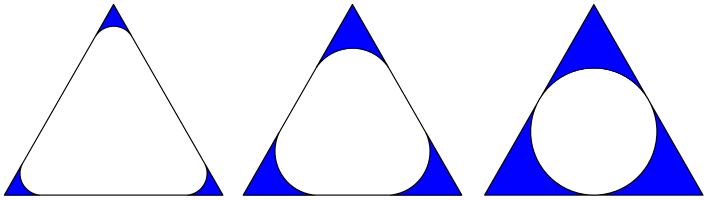

Fig.2 – Corner wetting films in a triangular capillary for decreasing capillary pressure (a) – (c). At (c) the swelling menisci meet and the films cannot swell further with decreasing capillary pressure. This is the threshold capillary pressure for snap-off.

In what follows we will refer to the wetting phase as water and the non-wetting phase as oil. Following Oren *et al*.[20] and Blunt *et al*.[24] the initial water saturation is assumed to be contained in clay and set *a priori*. The initial capillary pressure is set to 3000 kPa which sets a constant initial water film thickness throughout the network. Reducing the initial capillary by a factor of 10 has little effect on the initial water saturation and only a minor effect on the computed relative permeabilities. Water is injected over the inlet face of the network at a constant rate which sets the capillary number for the flood. Oil is free to leave the network from the opposite face. The oil pressure at the outlet face is held constant.

Pore-Scale Displacement Mechanisms

The pore-scale mechanisms by which water invades the network to displace oil have been described in detail [14, 20, 22]. They are based on the micromodel observations reported by Lenormand *et al.* [18]. We refer to them as *frontal displacements* of pores and throats – water invading oil filled pores and throats from a connected displacement front, and *snap-off* – water invading pores and throats ahead of the connected front by swelling and eventual rupture of corner films to produce water filled pores or throats. Snap-off is an important bond breaking mechanism and is responsible for large-scale trapping of oil in the network.

The threshold capillary pressure for frontal displacements of pores is given by Hughes and Blunt [16],

$$P_{c,f} = C_{In} \frac{\sigma \cos\theta}{r_p} \tag{1}$$

where σ is the interfacial tension, θ is the contact angle, r_p is the inscribed radius of the pore and C_{In} are input parameters [16] (C_{I1}=1.7, C_{I2}=1.15, C_{I3}=0.7, C_{I4}=0.5). This parametric expression accounts for the fact that the largest radius of curvature that can be achieved for a pore displacement depends on the number of adjacent oil filled throats, n (see Fig.3). Other expressions producing similar results have been proposed by Blunt [29], Oren *et al.* [20] and Patzek [22]. Eq.(1) also approximates the threshold capillary pressure for a frontal throat displacement with the pore radius replaced by the throat radius and the value of C_{In} approximately 2.

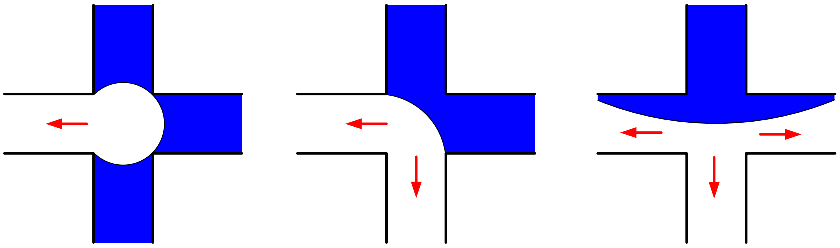

Fig.3 – Schematic of frontal pore filling mechanisms in imbibition. The threshold capillary pressure decreases with increasing number of connected throats filled with oil (I1-I3).

The threshold capillary pressure for snap-off is given by Hughes and Blunt [16],

$$P_{c,s} = \frac{\sigma}{r_t}\left(\cos\theta - \sin\theta\tan\alpha\right) \tag{2}$$

where r_t is the throat radius and α is the half-angle of the corners. Imbibition commences at a high capillary pressure and capillary pressure decreases during the course of the displacement. Pore-scale displacement events occur in order of decreasing threshold capillary pressure. The order in which frontal and snap-off displacements occur determines the pattern of the displacement and therefore the shape of the relative permeability curves and the value of the residual saturation. If the displacement is dominated by snap-off, relative permeabilities are low and residual saturations are high. If the displacement is dominated by frontal events trapping is low (low residual saturation) and relative permeabilities are high. The balance or competition between snap-off and frontal displacements is central to the description of imbibition displacements.

The ratio of threshold pressures for snap-off and frontal displacements is obtained from Eqs.(1) and (2),

$$\frac{P_{c,s}}{P_{c,f}} = \frac{1}{C_{In}}\left(\frac{r_p}{r_t}\right)\left(1 - \tan\theta\tan\alpha\right) \tag{3}$$

Eq.(3) shows that snap-off is favoured by high aspect ratios (large pores and small throats), small contact angles (strongly water-wet rocks) and small corner half-angles. Snap-off is also favoured by lower values of C_{In} i.e., snap-off is more competitive with frontal pore invasions when the pore is invaded from a smaller number of adjoining throats – low In.

Eqs.(1)-(3) also show the crucial role of contact angle and pore shape on the competition between snap-off and frontal displacements. The threshold capillary pressure for frontal displacements is always positive for $\theta<90^o$, Eq.(1). This means that frontal displacements can always occur. In contrast, Eqs.(2) and (3) show that the threshold capillary pressure for snap-off falls to zero when,

$$\tan\theta = \frac{1}{\tan\alpha} \tag{4}$$

and snap-off is entirely suppressed and the displacement is purely frontal.

Dynamic Effects

Quasi-static models ignore viscous effects so the capillary pressure at any pore or throat (the difference between the oil and water phase pressures) is constant throughout the network. The competition between snap-off and frontal displacements is therefore entirely determined by the value of the contact angle. In dynamic models of the type considered here [26] flow through wetting films in the corners of pores and throats introduces significant pressure gradients in the films ahead of the displacement front which change the available capillary pressure and therefore alter the order of displacement events. Fig.4 shows the effect of displacement rate on the competition between snap-off and frontal displacements for a two-dimensional network at different displacement rates or capillary numbers. The capillary number is defined as

$$Ca = \frac{\mu v}{\sigma} \tag{5}$$

where μ is the water viscosity and v is the displacement velocity. The pore and throat size distributions for the two-dimensional network were selected to give a high pore-throat aspect ratio (~ 8) and the contact angle was set to zero. These conditions strongly favour snap-off over frontal displacements.

At the lowest displacement rate (Ca=10^{-8}), where pressure gradients in the films are negligible, snap-off occurs throughout the network with almost no frontal displacements. This corresponds to the case of a quasi-static simulation where the capillary pressure is constant throughout the network. As the displacement rate increases (Ca=10^{-7}–10^{-6}) pressure gradients in the films increase and the region of the network ahead of the displacement front affected by snap-off contracts towards the displacement front (inlet face). Further increases in displacement rate (Ca=10^{-4}–10^{-5}) initiates significant frontal displacements and further contracts of the region affected by snap-off to the immediate vicinity of the displacement front. At the highest displacement rate (Ca=10^{-2}) snap-off is completely suppressed and the displacement is purely frontal. This corresponds to the case of a quasi-static simulation with all snap-off events disabled.

Eq.(3) shows that for a particular network (aspect ratio and pore shape or corner half-angle fixed) snap-off is suppressed by increasing contact angle. This is the only mechanism for suppression of snap-off in quasi-static models. Fig.4 shows that when the dynamics of film flow are included displacement rate becomes an additional important mechanism for the suppression of snap-off.

RESULTS AND DISCUSSION

Network Model Predictions of Relative Permeability

Fig.5(a) shows a comparison between measured oil/water relative permeabilities for strongly water-wet Berea sandstone [28] and the predictions of a quasi-static model reported by Blunt *et al.* [24] and Valvatne *et al.* [25]. The agreement was obtained using contact angles in the range 30^o – 90^o with an average contact angle of 60^o.

The actual experiments were conducted at a rate corresponding to Ca=$3.4\mathrm{x}10^{-6}$. Fig.5(b) shows a similar comparison for the dynamic network model and a contact angle of 30^o. The contact angle required to achieve a satisfactory match for the dynamic model is significantly smaller than for the quasi-static model because displacement rate plays an important role in suppressing snap-off. In comparing the quasi-static and dynamic models it should be noted that the quasi-static model employed a distribution of circular, square and triangular pore and throat shapes. The dynamic model predictions were made with all pores and throats having the shape of an equilateral triangle.

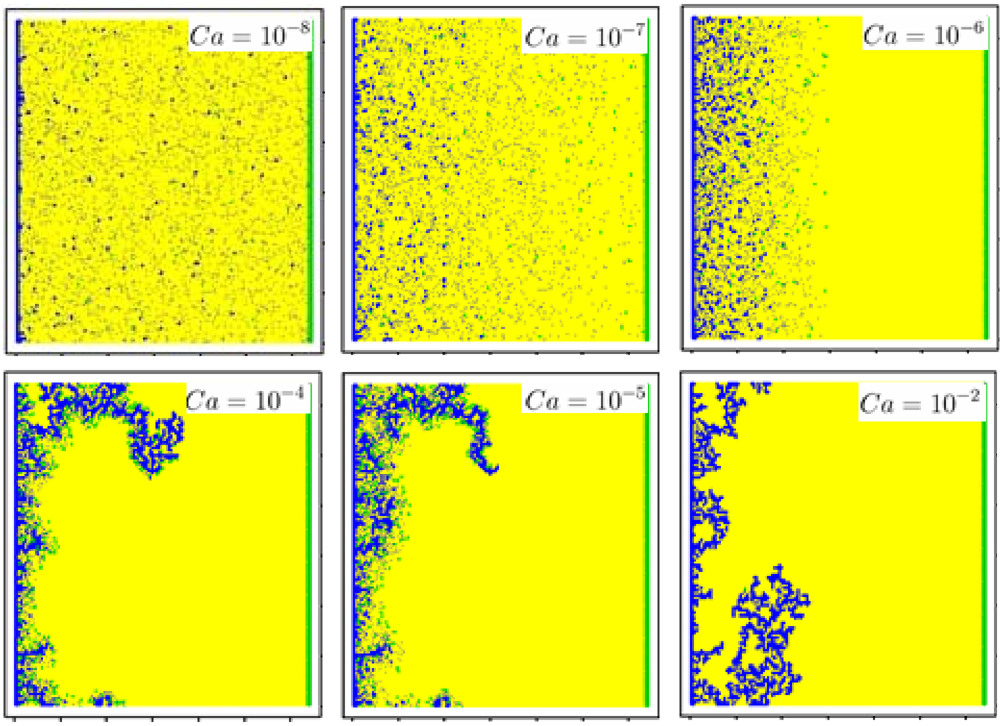

Fig.4 – Displacement patterns for a high aspect ratio two-dimensional network showing the effect of displacement rate on the competition between snap-off and frontal displacements.

Fig.5(b) also shows dynamic model predictions for a very high displacement rate ($Ca=10^{-1}$) where snap-off is completely suppressed and a very low rate ($Ca=10^{-7}$) where the displacement is dominated by snap-off. The difference between the relative permeabilities for the highest and lowest rates is small compared with the scatter in the experimental data. This insensitivity of relative permeability to displacement rate makes Berea a poor medium with which to assess the predictive value of quasi-static models for imbibition displacements.

It is also possible to achieve an approximate match to the measured relative permeabilities with a contact angle of zero and the experimental displacement rate as shown in Fig.6. In this case it is necessary to use a hexagonal pore shape. The film saturation at the point of snap-off for the triangular pores shown in Fig.5(b) is 22%. This is more than double that for the hexagonal pores in Fig.6 (9%). The thinner films for the hexagon pore shape are more effective in suppressing snap-off than the thicker films for the triangular shape at the same displacement rate. The competition between snap-off and frontal displacements is clearly a complex function of rate, contact angle and water film conductivity (thickness).

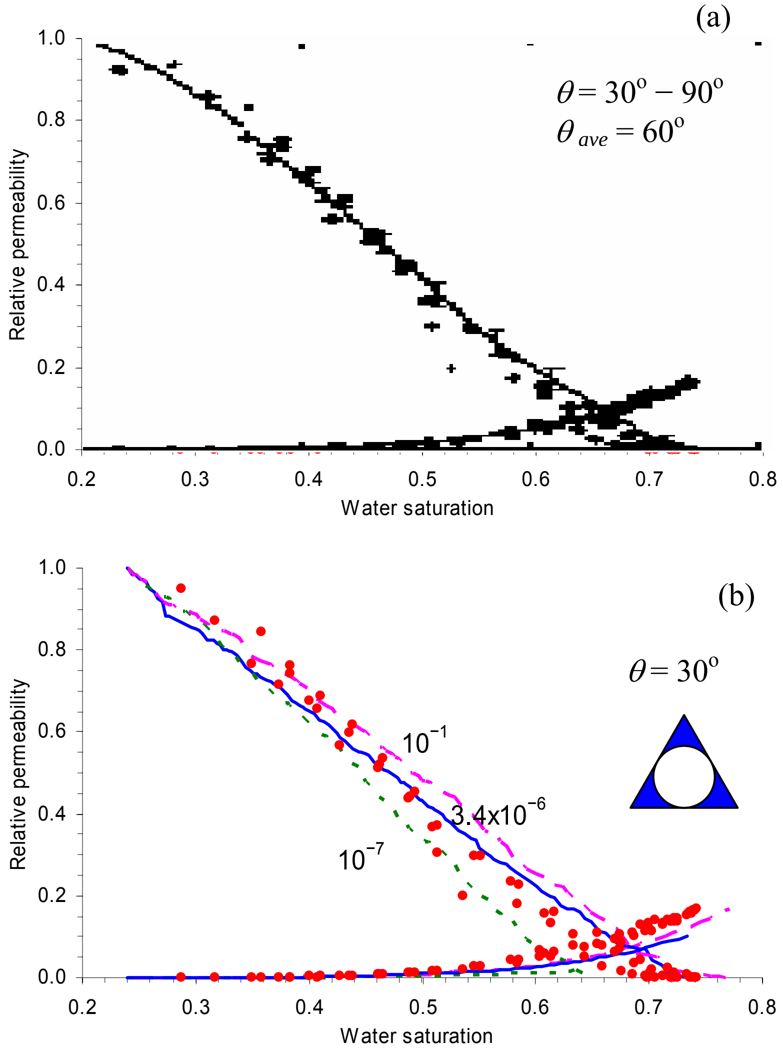

Fig.5 – Comparison between measured relative permeability for strongly water-wet Berea sandstone [28] and network model predictions. (a) Quasi-static model [24,25] – no rate effect. (b) Dynamic model of Nguyen *et al*. [26] using the experimental displacement rate Ca=3.4x10^{-6}.

Comparing the relative permeability curves shown in Fig.5(b) for the Berea network with those of Fig.7(a) for the modified Berea network shows the effect of pore/throat aspect ratio. The average aspect ratio for the Berea network is approximately 2 whereas that for the modified network is approximately 8 (see Fig.1). Increasing the aspect ratio causes an increased sensitivity of relative permeability to displacement rate. Fig.5 also shows the effect of contact angle on the sensitivity of relative permeability to rate. As the contact angle increases displacement rate becomes less important in suppressing snap-off and the sensitivity of relative permeability to rate decreases. For the triangular pore shapes used snap-off is completely suppressed for a contact angle of 60° and relative permeability becomes independent of rate (Fig.7(d)).

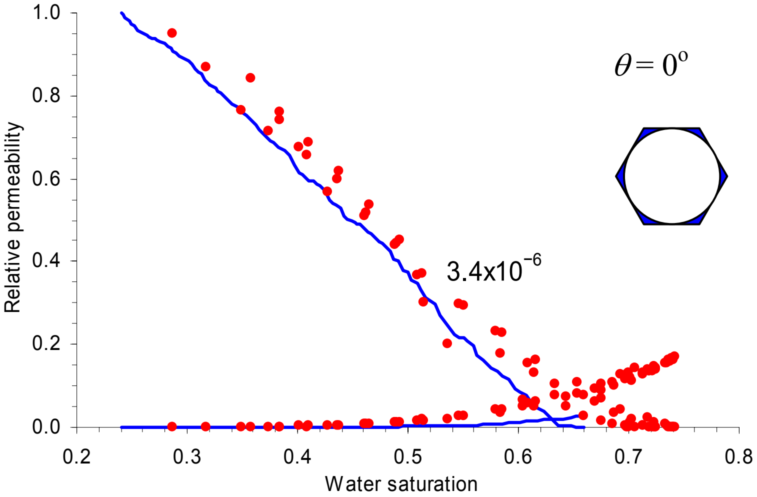

Fig.6 - Comparison between measured relative permeability for strongly water-wet Berea sandstone [28] and the dynamic network model of Nguyen *et al*. [26] using a zero contact angle and hexagonal pore shape.

Relevance to Laboratory Measured Relative Permeabilities

Laboratory measured relative permeabilities for Berea sandstone have been used to validate the predictions of quasi-static network models (e.g., [20-25]). Our calculations show that the low aspect ratio for Berea sandstone makes imbibition relative permeability for this type of rock insensitive to displacement rate and quasi-static and dynamic network models are expected to produce similar results for these conditions.

The laboratory studies which clearly conclude that imbibition relative permeabilities are independent of rate [3-7] were all conducted on strongly to intermediate water-wet Berea or similar high permeability homogeneous sandstones. The combination of low aspect ratio and moderate to high contact angles make relative permeabilities for these cores largely insensitive to displacement rate.

Mohanty and Miller [9] and Kamath *et al*. [10] measured rate dependent relative permeabilities and end-point saturations for low permeability highly heterogeneous preserved state cores. The overall trend is for relative permeabilities to increase and residual saturations to decrease with increasing displacement rate. The same trend is clearly evident in the computed curves discussed above. Although the pore/throat aspect ratio for the cores tested is unknown, it is not unreasonable to assume that it would be higher than for Berea given the low permeability and heterogeneity of the cores. The higher aspect ratio would suggest a greater dependence of relative permeability and residual saturation on displacement rate than for Berea.

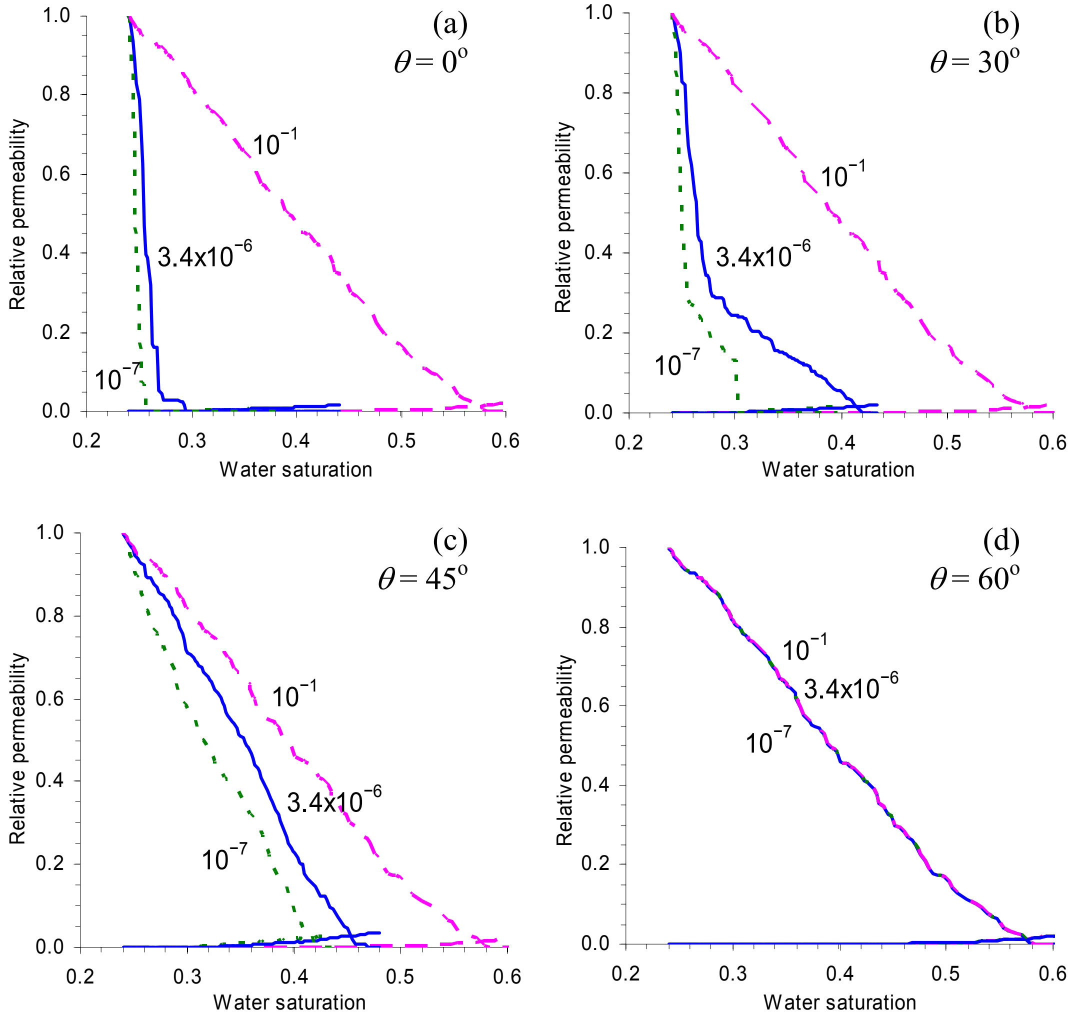

Fig.7 – Dynamic network model simulations for the Berea network with the modified throat size distribution shown in Fig.1(b).

Relative permeability data of the type reported by Heaviside *et al*. [8], Wang and Buckley [12] and Skauge *et al*. [13] is a little more difficult to resolve with the present network model. These data, mainly for sandstones, display little or no dependence of relative permeability and end-point values for strongly water-wet conditions but do show rate sensitivity for mixed-wet conditions. The present network model assumes uniform wettability conditions and does not include the additional pore-scale physics introduced by mixed wetting conditions which can result in the simultaneous existence of both water and oil films (e.g., see [21, 22, 24]).

Finally, in attempting to reconcile differences between different studies it is important to recognize the real experimental difficulties in measuring reliable relative permeability data in the laboratory. McPhee and Arthur [30] report a comparative study of four service laboratories using similar methods and cores. Measured relative permeability end-points for imbibition displacements varied from 10 to over 60 saturation units.

CONCLUSIONS

1. Displacement rate and contact angle affect the shape of imbibition relative permeability curves in a similar manner. Increasing contact angle and increasing rate increase relative permeability and decrease residual saturation.
2. The sensitivity of relative permeability to displacement rate and contact angle depends on the pore/throat aspect ratio. The sensitivity to rate is high for large aspect ratios and low for small aspect ratios.
3. The complex interaction between displacement rate, contact angle, aspect ratio and film conductivity (pore shape) makes it difficult to correctly interpret measured imbibition relativity permeability data.

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