A PORE NETWORK MODEL TO CALCULATE THE CAPILLARY PRESSURE AND RELATIVE PERMEABILITY CURVES OF INTERMEDIATE-WET RESERVOIRS

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ABSTRACT

In the present work, a pore-and-throat network including fractal roughness features along its surface is employed to simulate primary drainage and secondary imbibition by accounting for the quasistatic motion of menisci in pores and throats and varying the contact angle from 0^o (strongly water-wet conditions) to 180^o (strongly oil-wet conditions). The roughness features of pores and throats are circular cones and triangular prisms, respectively. The angle of sharpness of these features is decided by the specific surface area, and defines a range of contact angles within which the cross-section of the throat or the pore is occupied entirely by the one fluid (conditions of intermediate wettability). In contrast, outside this range, both fluids may coexist in a pore or throat. Such differences in the fluid distribution at the pore level may have pronounced effects on the calculated effective two-phase flow coefficients, and may relate their non-linear variation with the contact angle. The simulator is used to calculate the capillary pressure and relative permeability curves of a homogeneous rock as the pore system transits from strongly water-wet or strongly oil-wet to intermediate-wet.

INTRODUCTION

The wettability of porous media plays an important role in a variety of multiphase flow processes of industrial and environmental interest: the enhanced oil and gas recovery from reservoirs rocks; the contamination of the unsaturated and saturated zones of the subsurface by industrial wastes, landfill leachates, pesticides, etc, and the implementation of remediation technologies; the CO_2 storage in depleted reservoirs of hydrocarbons and deep saline aquifers for reducing the greenhouse gas effects. In industrial practice, the wettability of porous rocks is usually quantified by calculating the wettability indices which are obtained through the proper integration of capillary pressure curves (USBM methods, see for details Anderson, 1986a,b). Given that, the capillary pressure curves depend on the interaction of the pore structure, the wettability and the saturation history (Morrow, 1976), any effort for the interpretation of experimental data of relative permeability functions is inevitably associated with the analysis of the corresponding capillary pressure curves.

Many efforts have been made to predict the macroscopic transport properties of reservoir rocks using pore network models. An extended review of the majority of these models is given by Sahimi (1995).Theoretical simulations of the drainage / imbibition cycles in non-circular pores have described the creation of mixed-wet conditions by taking into account the disjoining pressure and the stability of the thin wetting films surrounding the rock grains (Kovscek *et al*., 1993). Numerous models and theoretical simulators have been developed to interpret the dependence of the two- and three-phase flow coefficients of porous media on the fractional / mixed wettability (Bradford *et al*., 1997; Hazlet *et al*., 1998; Blunt, 1998; Laroche *et al*., 1999; Dicarlo, 2000; Jackson *et al*. 2003). Nevertheless, no mechanistic model has ever been suggested to quantify the experimentally observed (Anderson, 1986a,b) non-linear variation of the two-phase flow coefficients as a strongly water-wet or oil-wet pore system becomes intermediate-wet.

In the present work, a pore-and-throat network incorporating fractal-like roughness features along the pore walls is used to simulate the pressure-controlled primary drainage and secondary imbibition in porous media. The simulator is used to examine how the capillary pressure curve, and the water and oil relative permeability functions change as the contact angle is varied from 0^o to 180^o, by placing emphasis on the contact angle range (60^o-120^o) of intermediate wettability.

PORE NETWORK MODEL

The pore space is modeled as a three-dimensional network of "spherical" pores interconnected through "cylindrical" throats (primary porosity) with roughness features (secondary porosity) superimposed on the free surface of pores and throats (Tsakiroglou and Payatakes, 1993). The pore-diameter distribution (PSD), the throat-diameter distribution (TSD), and the primary porosity, ε_p, are used as input parameters for the construction of the primary network, whereas the pore-wall roughness is modeled as a fractal-like surface (as described below) by using as parameters the total porosity ε_t, the number of layers of roughness features, i_p, and the ratio of the surface area of the secondary pores to that of the primary pores, r_A. Two opposite faces of the network serve as inlet and outlet faces whereas periodic conditions are imposed along the other four faces surrounding the cubic network. A water-wet membrane placed on the outlet face prevents the oil to escape from the pore network.

Fractal Roughness Model

For the cylindrical axisymmetric throats we consider that their rough surface is formed by superimposing successive layers of triangular prisms touching each other. For the spherical pores it is assumed that their surface is covered by successive layers of right circular cones arranged in a closed packed layer. The parameters of the model are: (1) the number of rough features per linear dimension of a roughness feature of the previous layer, n_r; (2) the number of layers of roughness features, i_p; (3) the common angle of sharpness of roughness features, w. It is worth noting that $w=w(i_p,r_A)$ and $n_r=n_r(i_p,\varepsilon_p/\varepsilon_t)$. A detailed description of the pore-wall roughness model is reported by Tsakiroglou and Payatakes (1993).

SIMULATION OF DRAINAGE AND IMBIBITION

Drainage is a process where a non-wetting fluid displaces a wetting one at increasing values of the capillary pressure, whereas the reverse process is defined as imbibition The contact angle measured with respect to aqueous phase (brine), θ, is used to quantify the wettability of a pore network. If $\theta \le \pi/2$ then the pore network is defined as water-wet, and if $\theta > \pi/2$ the pore network is defined as oil-wet. In a water-wet case, initially the pore network is occupied by brine (aqueous solution of an electrolyte) which is gradually displaced by oil. In contrast, in an oil-wet case the defender is oil and the invader is brine.

Drainage in Water-Wet Networks

At a current value of the capillary pressure, the pore network is scanned in search of throats that are accessible to the external oil sink and have a size that allows a meniscus to penetrate into them. As soon as a throat is filled with oil, the adjoining water-occupied pores are invaded by oil spontaneously. The procedure is repeated until no more meniscus move, and capillary equilibrium is established. Then a pressure difference is imposed across the network and the Kirchoff rules are applied separately to the equivalent electric sub-network of each phase. From the numerical solution of the resulting system of coupled linear equations, the pressure of each phase at the centre of each pore and the flow rate of the wetting and non-wetting phases at each unit cell are calculated; the Darcy law for two-phase flow is then used to determine the water and oil relative permeabilities.

Additional assumptions that are adopted to simulate drainage in water-wet networks are summarized below.

(a) Water drains from a throat or pore only if there is a non-interrupted column of water connecting it to the external water sink.
(b) Water remaining along pore-wall roughness can drain as long as its hydraulic continuity is preserved.
(c) Occasionally, blobs of trapped water may be created after the filling of a pore with oil.
(d) The pore network becomes hydraulically conductive to oil after the breakthrough pressure, when a network spanning cluster of oil-occupied pores and throats is created for the first time.
(e) The analytic solution of the simultaneous flow of two immiscible fluids through a cylindrical tube is employed to calculate the hydraulic conductance of oil and water in throats and pores that are occupied by both fluids. Equivalent hydraulic diameters are assigned to throats and pores in proportion to the volume fractions of the two phases.

(f) If $\theta \geq \pi/2 - w$, then the penetration of a meniscus in a roughness feature follows unstable interfacial configurations of decreasing mean curvature (the equilibrium capillary pressure is negative and decreases as the saturation of the non-wetting fluid increases). Therefore, all roughness features are fully occupied by oil, with the result that neither pores and throats occupied by trapped blobs of water, nor oil-occupied pores and throats contribute to the hydraulic conductivity of water.

Drainage in Oil-wet Networks

An analogous approach based on similar assumptions is used to simulate drainage in an oil-wet network. The most important differences are outlined below.

(a) The hydraulic conductance of pores and throats, occupied by both fluids, are calculated by the aforementioned approach of the two-phase flow in a capillary tube, by simply interchanging the spatial arrangement of the two fluids.

(b) If $\theta \leq \pi/2 + w$ the roughness features are occupied completely by water, otherwise oil films are left around invading water.

Simulation of Imbibition

After the end of a drainage run, the saturation of the wetting fluid has reached its irreducible value, S_{wir}. As the capillary pressure starts decreasing, the wetting fluid (water or oil) may imbibe into pores of progressively larger size depending on their accessibility properties. However, it is well-known from earlier experimental and theoretical studies (Tsakiroglou and Payatakes, 1990; Tsakiroglou *et al*., 1997) that at sufficiently low capillary pressures, thin films of wetting fluid surrounding the non-wetting fluid may collapse in narrow throats, because of capillary instability, by the "snap-off" mechanism. The critical capillary pressure for snap-off depends on contact angle, and throat geometry (Tsakiroglou *et al*., 1997). The pore-level events that are taken into account in the simulation of imbibition are outlined below

(a) The wetting fluid may imbibe into a throat that is occupied by the non-wetting fluid through one of the following events:

- (i) piston-type displacement, if a meniscus exists at one of the throat ends, the non-wetting fluid is accessible to the external sink, and the capillary pressure is lower than the critical value given by the Washburn equation,
- (ii) snap-off, when the non-wetting fluid is accessible to the external sink, and is surrounded by a film of wetting fluid occupying the pore-wall roughness, whereas the capillary pressure is lower than the critical value for snap-off.

(b) Wetting fluid may imbibe into a pore if at least one meniscus exists at one junction of the pore with adjacent throats (which means that at least one of the adjoining throats is occupied by wetting fluid) and the capillary pressure is lower than the critical value given by the Washburn equation.

RESULTS AND DISCUSSION

A pore-and-throat primary network having the skeleton of a regular cubic lattice was constructed by using log-normal pore (PSD) and throat (TSD) diameter distributions (Table 1). After examining the variation of the number of features, n_r, with the total porosity and the angle of sharpness, w, with the surface area ratio, r_A, the parameter values shown in Table 1 were selected. The calculated values of permeability, k=443 mD, and formation factor, F=12.5, are typical for sandstones.

Under water-wet conditions, the critical contact angle $\theta_c = \pi/2 - w$ (=1.19 rad=68.4^o) defines a threshold value above which no water is left in pore-wall roughness and water saturation reaches its irreducible value at relatively low capillary pressures (Fig.1a). For $\theta \geq \theta_c$ the high pressure part of the capillary pressure curve disappears and information concerning the sizes and volumetric percentage of the roughness porosity is lost (Fig.1a). Instead, for $\theta < \theta_c$ information concerning the structure of the secondary porosity is reflected in the capillary pressure curve (Fig.1a).

The plateau of the oil relative permeability, $k_{ro}(S_w)$, at low water saturations is associated with the small change of the oil hydraulic conductivity as the thickness of the wetting films remaining in the pore-wall roughness is reduced (Fig.1b). At decreasing values of the contact angle the thickness of the films remaining in pores or throats after oil invasion decreases so that the plateau gradually shrinks, and disappears entirely when $\theta \geq \theta_c$ (Fig.1b). The water relative permeability $k_{ro}(S_w)$ at low water saturations is also due to the presence of films of wetting fluid along roughness features, and as soon as these films disappear ($\theta \geq \theta_c$) the relative permeability decreases dramatically (Fig.1b).

Secondary imbibition from a water-wet pore network that has been filled under a receding contact angle θ_R=20^o was simulated without including the mechanism of the snap-off in throats (Fig.2a,b). Under intermediate-wet conditions, $\theta_A \geq \theta_c$ (θ_A=advancing contact angle), the oil/water interfaces in roughness features are pinned on the solid surface, no water expels from roughness features at positive capillary pressures, and imbibition takes place over a narrow pressure range (Fig.2a). On the other hand, the relative permeability curves tend to become independent of the particular value of the contact angle, and depend only on whether the fluid system is water-wet, $\theta_A < \theta_c$, or intermediate-wet, $\theta_A \geq \theta_c$ (Fig.2b).

CONCLUSIONS

In the present work, mechanistic simulators of oil/water drainage and imbibition in pore-and-throat networks were developed to quantify the capillary and hydraulic properties of intermediate-wet ($\pi/2 - w \leq \theta \leq \pi/2 + w$) porous media, and to give a physical interpretation of the non-linear dependence of the multiphase transport properties on wettability. The capillary pressure curves are always sensitive to the wetting state and the particular value of the contact angle. The relative permeability functions for secondary imbibition have the tendency to be grouped in families of curves which are sensitive mainly to the contact angle range (water-wet state / intermediate-wet state) rather than to the particular value of the contact angle.

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Table 1. Parameter values of the pore-and-throat network.

Parameter	Value	Parameter	Value
TSD: $\langle D_t \rangle$ μm	10.0	Total porosity, ε_t	0.20
σ_t μm	3.0	Number of features, n_r	20
PSD: $\langle D_c \rangle$ μm	30.0	Surface area ratio, r_A	100
σ_c μm	8.0	Angle of sharpness, w (rad)	0.376
Primary porosity, ε_p	0.15	Number of layers, i_p	4

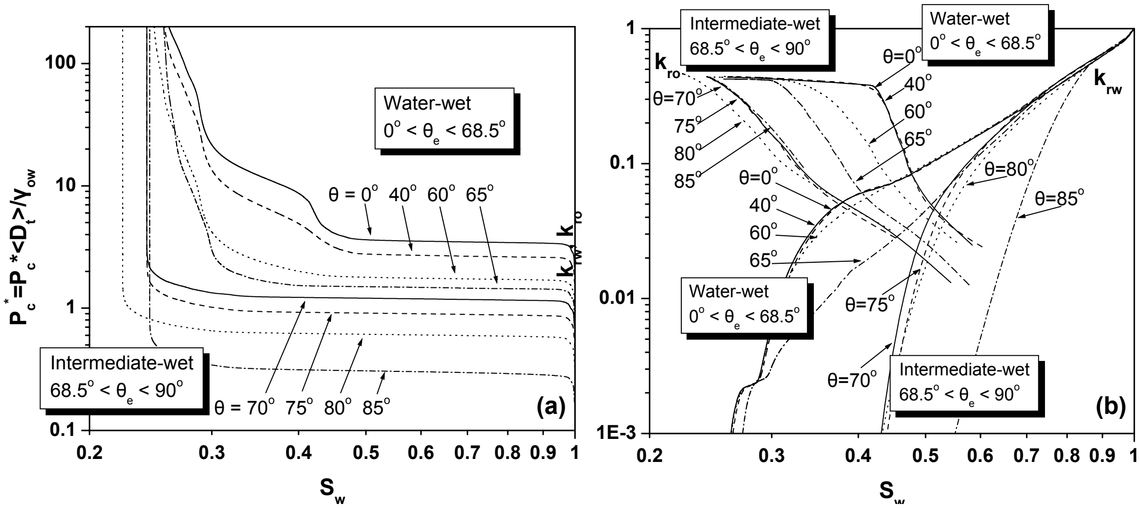

Figure 1. Simulated (a) capillary pressure curves and (b) relative permeability curves as functions of the contact angle for drainage in a water-wet pore network

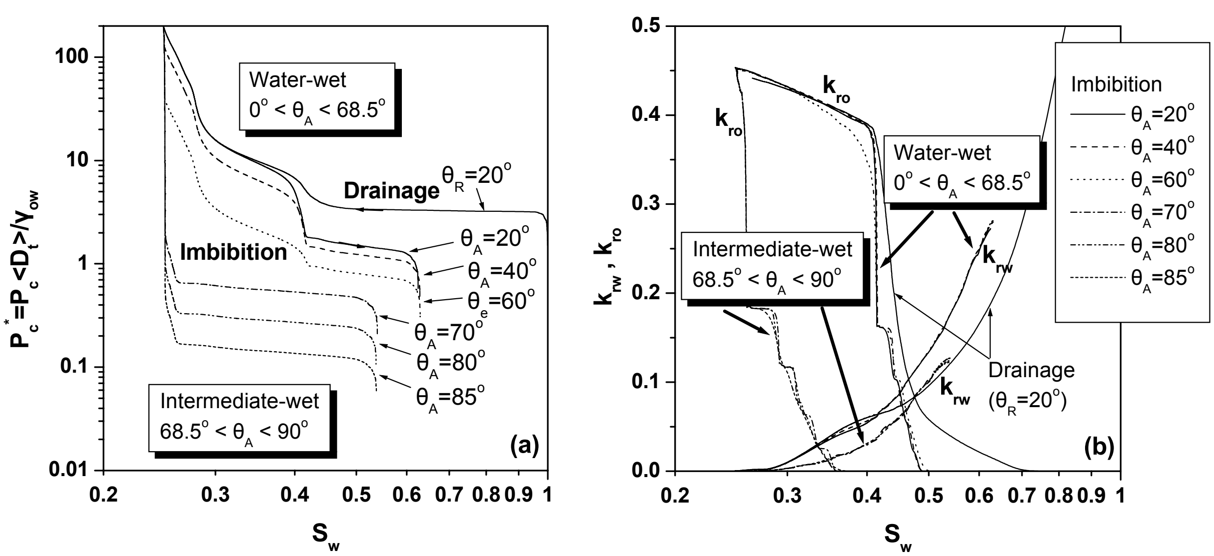

Figure 2. Simulated (a) capillary pressure curves and (b) relative permeability curves as functions of the contact angle for imbibition in a water-wet pore network (without including snap-off in throats)