DYNAMIC CAPILLARY NETWORK MODEL OF IMBIBITION

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Abstract. *Multiphase flow in porous media is important in many areas of science and technology, such as petroleum reservoir and environmental engineering. For an accurate and reliable estimation of the macroscopic properties of the flow, it is necessary to have full understanding of the microscopic flow mechanisms at the pore level and a realistic representation of the porous medium. One way of to incorporate these two aspects is through capillary network model. In this work, we develop an unstructured 3D network model, as shown in Fig. 1, to study the dynamics of imbibition process. The unstructured network used in the analysis was constructed based on images obtained from tomography scanning of real porous samples and it is available for download from Imperial College. The two-phase dynamics model was used to study the effect of viscosity ratio and porous structure (different networks were used to describe a sandstone and carbonate samples) on stability of the displacing front and the relative permeability curves.*

Keywords*: Emulsion flow, enhanced oil recovery, dynamic modeling, imbibition.*

1. INTRODUCTION

Emulsion can be formed in oil reservoirs during oil recovery process by chemical or even water flooding. In addition, emulsion with specific formulation can be used in enhanced oil recovery processes as a blockage agent in preferential flow paths (Romero et al., 1996), diverting the flow for the non-swept regions of the porous medium. This method have been studied for the main purposes of increase the oil recovery factor, with the advantage of reduce the water-oil ratio in some steps of the oil production.

The analysis of emulsion flow in the porous media is a challenging subject, due to a strong dependence on the characteristics of the pore space and mainly due to the complex mechanisms of displacement of fluids and particle dynamics.

The prediction of macroscopic transport properties of emulsion can be achieved by developing numerical simulations using capillary network models. It is an enormously profitable way of obtaining representative parameters of the physics of the pore-level dynamics and that can be used in a multiphase equation to describe effective, large-scale behavior.

Starting from single-phase simulations, it is possible to test the network properly and to determine the initial features necessary for an accurate flow description. However, when more than one fluid is present in the porous media, the presences of fluid interfaces affect the flow in many manners. Special types of displacement of fluids and formation of trapped blobs are commonly observed in porous media. Even these more simple phenomena in multiphase flow are not completely described by the equations of motion. This work applies a combination of a theoretical and experimental analysis and with specific rules for flow in numerical study.

Concerning emulsion droplets effects, there are two basic mechanisms of drops capturing in the porous medium. Firstly, by straining the drops with the same order of magnitude of the throats plugs up this narrow passage, diverting the flow to other paths. However, it can be deformed and squeezed through this narrows throats. Another important phenomenon is the direct interception of smallest drops on the pore walls. It can occur as a result of different types of forces, like hydrodynamic forces and even electrical attraction, and is affected by fluids velocity, ionic strength, pH of the continuous phase and drops density and concentration. Different works on the literature tried to develop reliable methods for accounting both this features of the emulsion flow, considering particle interaction probability and empirical parameters (Rege and Fogler, 1986; Soo and Radke, 1986a,b).

Recently, another physically based approach has been used to determine the emulsion flow properties, relating the increase of pressure drop due to the presence of emulsion droplets in the flow to the ratio between drop and capillary diameters, viscosity ratio and flow rate (Martinez and Udell, 1990). However, it seems that an accurate model is still not available. In this work, we use data obtained from experiments on flow of emulsion in a constricted capillary tube. The microscopic behavior of the drops related by this method is considered in the overall flow in a disordered capillary network. Thus, it is possible to obtain relevant dynamic properties of the emulsion flow, which can be incorporated in the macroscopic flow analysis for enhance the oil recovery factor.

2. DYNAMIC NETWORK MODEL

2.1. Network description

The capillary network consists in void nodes interconnected by capillary tubes, which represent the complex geometry of the porous medium (Fatt, 1956). In this work, it is used a more realistic network model (Bakke S. and Øren P. E., 1997), containing all the important characteristics of a real sample. For each element (node or throat) is assigned an inscribed radius, a total volume and a length, used in the conductance computations. Furthermore, each one have a shape factor (ratio do the cross-sectional area to the perimeter squared) and can have scalene triangular, square or circular cross-section. A sketch of a capillary network representing a real sample is shown in Fig. 1.

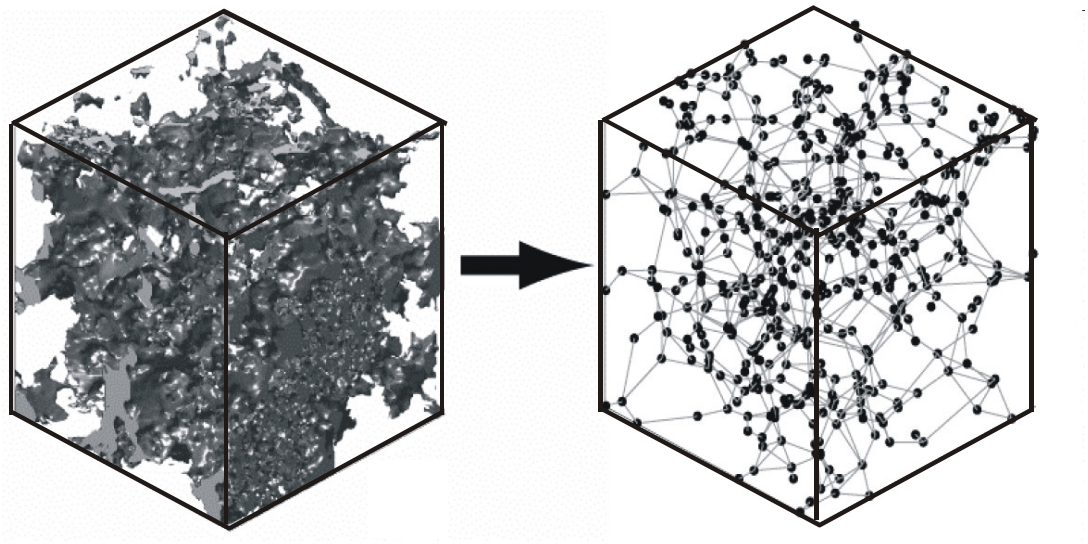

Figure 1. A simplified network representing a reservoir rock sample

The porous medium is initially saturated with the non-wetting phase. As a boundary condition, constant flow rate is imposed at the inlet face, and the atmospheric pressure at the outlet face is set to zero.

In Tab. 1, it is listed the fundamental characteristics of the network used in this work, representing a Berea sandstone rock sample.

Table 1. Network statistics

Item	Throats	Nodes	Total
Number	26146	12349	38495
Porosity (%)	4.56	13.74	18.31
Square cross-section (%)	7.54	4.34	6.51
Circular cross-section (%)	1.73	0.17	1.23
Triangula cross-sections (%)	90.72	95.51	92.26
Minimun radius (μm)	0.90	3.62	0.90
Average radius (μm)	10.97	19.16	13.60
Maximum radius (μm)	56.85	73.53	73.53
Average cordination number	-	4.19	-
Maximum cordination number	-	19	-
Volumn (mm^3)	-	-	27

2.2. Flow calculation

The emulsion is assumed dilute, stable even in the case of low interfacial tension and the continuous phase is assumed Newtonian. The conductance are computed considering Stokes flow and perfect wettability of the wetting phase (θ=180º).

As in the work of Van der Marck et al. (1997), our model had no capillary pressure term for pore-scale imbibition, so the flow rate is directly proportional to the pressure difference between wetting and non-wetting phases.

For single-phase, incompressible flow within throats with uniform cross section, the Poiseuille's law relates flow rates across each throat to the pressure drop between two nodes. Throat-nodes entry effects and losses were neglected in conductivity computations (Dullien, 1977). Considering simulations at a high flow rate and small node-to-throat ratio the snap-off mechanism can be neglected.

For a single-phase flow, the conductance G is given by:

$$G_i = \frac{Ar^2}{8\mu_i L} \tag{1}$$

The total fluid conductance between the pore *i* and *j* is given by the harmonic mean between the conductance of the throat and both nodes. The conductance of the thin film of wetting phase is also calculated (for more details, see Hui and Blunt, 2000)

It is known that the local imbibition processes are determined by the nodes capillary pressures. Thus, the mass conservation at each node gives a set of equations similar to Kirchhoff's equations for resistor networks.

$$\sum_{n=1}^{N_{neighbor\ pores}} Q_{i,j} = 0 \tag{2}$$

The pressure drop between two nodes determines the mass flux between them. For a single-phase flow, the described problem can be written as a linear matrix problem, which must be solved for the pressures at each node. Finally, the volumetric flow rate can be obtained by the Eq. (3).

$$Q_{i,j} = G_{i,j}\Delta P \tag{3}$$

Some important parameter are being estimated, as for example both absolute and relative permeability, shape of the advancing fluid interface and influence of the another networks representing different topological arrangements.

2.3. Interface advancing

When two immiscible fluids are present in the porous medium, the flow description becomes more complex due the introduction of capillary pressure. In capillary-dominated flow, when we have low capillary number ($Ca \sim 10^{-6}$), the percolation theory (Sahimi, 1994) can be applied. In viscous-dominated, the diffusion-limited aggregation model is necessary to describing the flow. Both of them are rule-based models, devised to update the fluid configuration and to honor the pore-level physics.

In a general two-phase flow, a Dynamic Network Model are required, where a combination of rule-based and resistor type model are performed to estimate a pressure field at each time step to account for the viscous pressure drop, while immobilizing the interfaces (Koplik and Lassester, 1984). This makes the problem more computationally intensive. Moreover, if a wetting phase displaces a non-wetting phase (or vice-versa), the irreversible redistribution of fluids in the formed meniscus makes the flow equations non-linear. Thus, it is necessary to use the pressure field from the previous time step, P_{old}, to calculate the new conductance for each throat. It is similar to the Implicit in Pressure Explicit in Saturation scheme - IMPES (Aziz and Settari, 1979).

2.4. Model for the emulsion flow

We used experimental data obtained by Cobos, Carvalho and Alvarado (2009). They injected oil-in-water emulsions in a single capillary tube. A blockage factor (*f*) as a function of the capillary number was used to account for the partial or total pore blocking due to the drop-pore wall interaction. For that specific type of emulsion, was found that the blocking occurs if the local capillary number is smaller than a critical value (Ca = 0.008). If the local capillary number is higher than this value, the pressure gradient is sufficient for dislocating the drop through the tube, although it causes a local permeability reduction, represented in this work by means of the Eq. (1), where μ_{eff} represents the local, effective

viscosity and μ_{cf} is the viscosity of the continuous phase . Yet, this blockage factor is a depending on the drops to throat radius ratio, r_d / r_t , as shown in the Eq. 4.

$$\mu_{eff} = \frac{\mu_{cf}}{f(r_d / r_t, Ca)} \tag{4}$$

Before we can estimate the flow rate when injecting emulsion in the network, it is extremely necessary to study the non-linear behavior of the factor *f* when considering emulsion flow in constricted capillaries. As the blockage factor is a function of the pressure drop, as one can see in Eq. 5, it is necessary to recalculate the pressure field in all pores as well as the conductances and flow rate in each capillary of the entire network. These second flow rate is calculated considering the blocking provided in the first flow rate calculated. Thus, by the we use iterative calculations for obtain the real blocking effect. These makes the problem much more computationally intensive.

$$Q_{i,j} = f(Q).G_{i,j}\Delta P \tag{5}$$

In this work, the main goal is to qualitatively reproduce macroscopic behavior, since the available amount of data on this approach is not enfough to the statement of an accurate blockage function *f*. The shape of the function obtained can be seen in the Fig. 2. Notice that this parameter predicts pore blocking only for $r_d / r_t > 0.85$. It does consider mainly straining dominated entrapment in the throats. We also make use of another empirical parameter that is supposed to account for drops attraction and capture by the pore walls (for more details, see Romero, M.I., 2009).

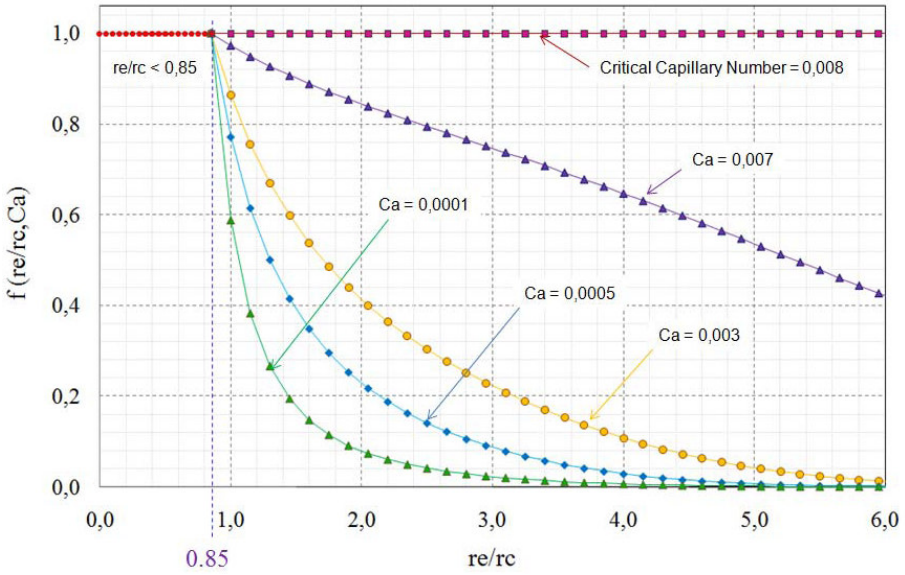

Figure 2: Blocking factor, *f*, at different capillary numbers.

3. RESULTS AND FUTURE WORK

Figure 3 shows a qualitative result for comparison of the oil recovery factor as a function of the type of fluid injected: only the continuous phase of the emulsion, representing simplest water flooding; emulsion with very small drops of oil, for which little effect is observed in oil recovery, and emulsions with major drop size.

In the limit case, where the radius of the drop is almost equals to the average throat radius, one can see that the maximum oil recovery is reached earlier than for injecting drops with smallest sizes. This symbolizes a more flat advancing front and the bigger oil recovery is easily seen. However, is s necessary to incorporate more displacement mechanisms for better representing of the dynamics of multiphase flow within the network.

Flow in the pore scale cannot be described by an effective viscosity. More realistic two-phase flow models to describe the emulsion flow in the pore scale are necessary. It is our contention that despite the progress in the study of emulsion flow in porous media, detailed analysis at the pore-scale is still required to develop reliable models of emulsion flow through porous media.

The blockage mechanism considered has been characterized by the average response to the flow of emulsion in comparison with the flow of continuous phase. The results indicate the effect of the dispersed phase in the tube constrictions represented in the network and can be use as an initial step to the better understanding of how the emulsion drops can do the whished selective blockage. Other subject of interest is the influence of the drops concentration in EOR processes.

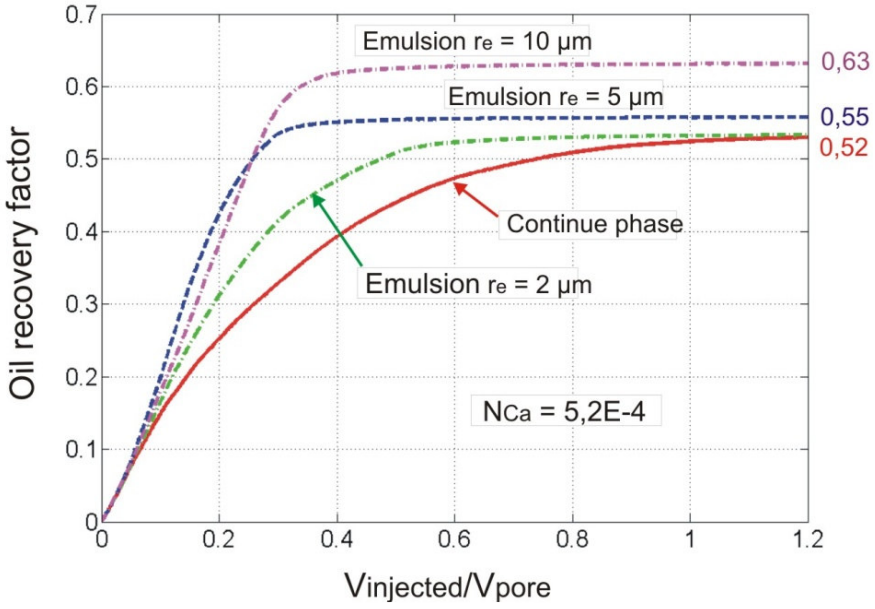

Figure 3. Initial results for the network simulation

As more effort needs to be done in two-phase flow analysis, some rules for displacement must be developed for considering the flow in clay films and corners. However, the initial results are promising, showing that emulsions can be used for enhanced-oil recovery.

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