NETWORK MODEL OF EMULSION FLOW IN POROUS MEDIA

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Abstract. *Transport of emulsions in porous media is relevant to several subsurface applications. Many enhanced oil recovery processes involve emulsion formation and their flow in some form. Modeling the flow of emulsion in porous media is extremely challenging. The available descriptions based on effective viscosity are not valid when the drop size is of the same order of magnitude as the pore-throat size. In this case, drop straining and capturing may partially block the pore passage and an accurate model should be able to describe this local changes on mobility. The model developed in this work is based on the flow rate-pressure drop relation of emulsion flow through constricted capillaries. A capillary network model is constructed in order to obtain macroscopic parameters from upscaling of the microscopic behavior. The results show how the permeability changes with Darcy velocity and emulsion properties. At low flow rates, the large drops partially block the smallest pores, leading to a low permeability. At high flow rates, the pressure gradient in each capillary is strong enough to force the drops to flow through the constrictions. Consequently, the permeability rises with capillary number. The results agree well to experimental measurements in sandstone cores.*

Keywords*: Emulsion; Network Modeling; Capillary Number; Porous Media*

1. INTRODUCTION

Transport of emulsions through porous media is relevant to several subsurface applications. Emulsions play an important role in many EOR processes. If the dispersed phase drops flow through the pore space such that they can partially block the already swept more permeable paths, they could divert the flow of injected water to unswept regions, leading to more efficient reservoir sweep and higher recovery factor. Seright and Liang (1995) review the advantages and disadvantages of different blocking agents, including emulsions. They conclude the emulsion could approach properties similar to low viscosity gelant. Thomas and Ali (1989) carried out experimental investigation of the injection of oil-in-water and water-in-oil emulsion in porous media. They concluded that the mobility of emulsions is strongly dependent on its drop size distribution, quality and rheology for a given pore size distribution.

Modeling the flow of emulsion in porous media is extremely challenging. The available descriptions based on effective viscosity are not valid when the drop size is the same order of magnitude of the pore throats. In this case, drops can partially block the pore passage, as discussed by Soo *et al.* (1986a, 1986b and 1984). They proposed a filtration model describing the flow of stable, dilute emulsion in unconsolidated porous media; they quantitatively tested the proposed model against experimental data on transient permeability obtaining a good agreement. They also investigated the possible roles of velocity in the transport of emulsion through porous media and concluded that at low capillary numbers, the emulsion flow behavior is at most a weak function of velocity. This local change on mobility should be a function of the local capillary number, in the extreme case of very high capillary number, there is no need for an extra pressure difference to deform the drop and there is no effective blockage.

Here we analyze the flow of emulsion through porous media in experiments and in simulations in a capillary network model. The experiment consisted of displacing an emulsion with known drop size distribution through two sandstone cores with different permeability values. The pressure drop-flow rate relationship was determined in these experiments.

The network model developed in this work is based on the flow rate-pressure drop relationship of emulsion flow through constricted capillaries. Cobos *et al.* (2009) studied the flow of oil-in-water emulsions through a converging-diverging quartz capillary tube (25 μm pore-throat radius) that represented a pore-throat model.

A capillary network model is constructed in order to obtain macroscopic parameters from upscaling of the microscopic (pore level) behavior. Any theoretical or numerical approach to this problem not only needs a detail understanding of the emulsion injection mechanism at the microscopic level but also an accurate and realistic characterization of the structure of the porous medium.

2. EXPERIMENTAL ANALYSIS

2.1. Definition of emulsion

Emulsions are dispersions of two immiscible liquids, such as oil and water. Emulsions normally contain a third component, that is, an emulsifying agent, which has two important functions, namely: (1) to decrease the interfacial

tension between oil and water, thereby enabling easier formation of the emulsion; and (2) to stabilize the dispersed phase against coalescence once it is formed. In crude oil emulsion, the emulsifier may be derived from the oil itself, e.g., asphaltenes and naphthenic acids; or from the producing formations, e.g., clays and, silica particles. An acid or base may react with a crude oil to produce an emulsifier. In this work, we added a surfactant (SDS) to the water phase.

2.2. Emulsion preparation

The oil-in-water emulsions used in the experiments had the following composition: the continuous phase was a 30% water and 70% glycerin ($C_3H_3(OH)_3$) mixture. A surfactant, Sodium dodecyl sulfate, at 3 times the critical micelle concentration (CMC) was used. The typical molar value of 1CMC for this surfactant is $8.1x10^{-3}$ or approximately 2.3g/l. Synthetic oil, Tivela S-460, was used as the dispersed phase at a volumetric fraction of 10%. Table 1 presents the properties of each phase. The oil and water + glycerin + surfactant mixture was sheared in a homogenizer. The rotation of the dispersing tool and the time of mixture were used to control the drop size distribution of the emulsion. The drop size distribution was measured using a Mastersizer 2000 (Malvern Instruments).

Table 1. Properties of each phase

Fluid	Density(g/ml)	Viscosity (cP) at 25ºC	Superficial Tension (mN/m)
Continuous	1.1769	22.5	30.7
Dispersed	0.9949	950	28.3

An oil-in-water emulsion, labeled Small-Drop, was prepared by dispersing oil-in-water using a rotation rate of 24,000 rpm for 30 seconds; the drop size distribution is show in the fig. 1.

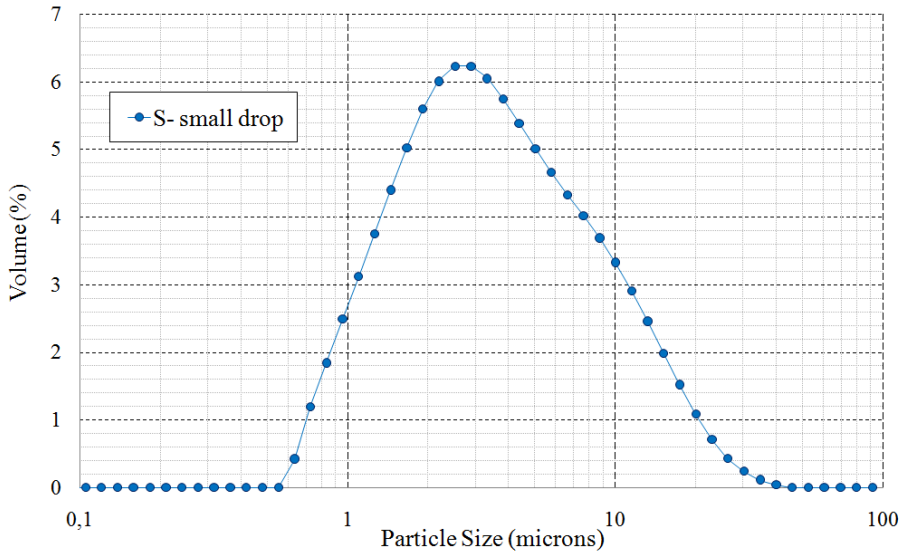

Figure 1. Drop size distribution of the emulsions with small drop size

2.3. Core folding experiments

Prior to injecting the emulsions, the sandstone cores were weighted before and after being saturated with distilled water. With these data and the dimensions of the cores, the porosity and pore volume were determined. The cores were then inserted in a rubber sleeve and placed in the core holder unit. The permeability of each core was determined by measuring the volumetric flow rate of water as a function of the pressure drop across the cores. Table 2 presents the properties of the two cores used

Table 2. Core properties

Core	Pore Volume(ml)	Porosity (%)	Permeability (mD)
M	23.024	27.1	124.36
H	17.159	31.8	901.6

The emulsion was injected into the sandstone cores, initially saturated with distilled water. The emulsion was injected using a positive displacement pump, and the flow rate was controlled by the rotation of the microgears. The pressure upstream the core was registered as a function of time until a steady state condition was reached. The drop size distribution of the produced emulsions was also measured. Figure 2 sketches the experimental apparatus used and details of the core sample and inlet and outlet plates are show in Fig. 3.

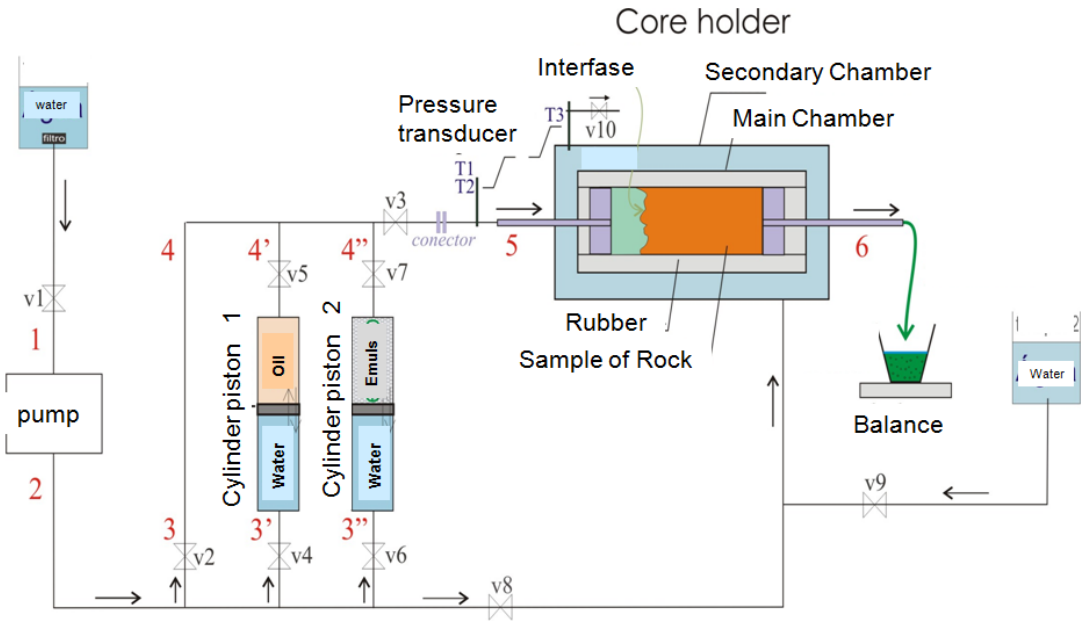

Figure 2. Schematic representation of the experimental apparatus

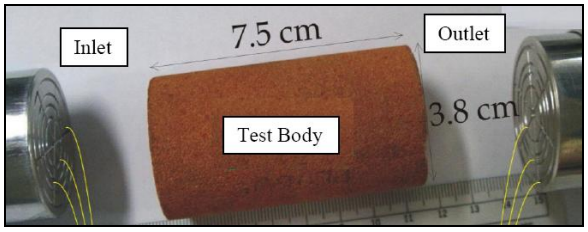

Figure 3. Sandstone sample (Sample of Rock in the Fig. 2)

2.4. Results

Emulsion was injected into the cores at constant flow rate until the pressure drop between inlet and outlet reached a steady state, which in some cases happened after many pore volumes of emulsion was injected. The results are presented in terms of an apparent viscosity μ_{app}, defined as:

$$\mu_{app} = \mu_N \frac{Q_N}{Q_T} \tag{1}$$

where Q_T is the imposed flow rate and Q_N is the flow rate that would be obtained with the same pressure drop with a Newtonian viscosity μ_N .The apparent viscosity is presented as a function of the capillary number, defined as:

$$Ca = \frac{U\,\mu_{CF}}{\sigma_I} \tag{2}$$

where U is the Darcy velocity U = Q_T /A_T, A_T is the cross sectional area of the sample rock, μ_{CF} is the viscosity of the continue phase and σ_I is the interfacial tension between the continuous and dispersed phases. The apparent viscosity of the injected emulsion as a function of capillary number for both cores is shown in Fig. 4. It falls as the capillary number

rises for both cores. This dependence on capillary number is evidence that the partial blocking mechanism is a function of the ratio between viscous to surface tension forces. At low capillary number, surface tension forces are relatively strong, and a high extra pressure difference is necessary to squeeze the large drops through the pore throats, leading to high apparent viscosity. The effectiveness of the blocking mechanism falls as the surface tension forces become weaker. The results also show that the partial blocking is a strong function of the size of the pore throat relative to the drop diameter. The apparent viscosity of the emulsion on the flow through the less permeable cores is higher. A large extra pressure difference is necessary to deform the drops through the smaller pore throats. Experiments with the core labeled M (less permeable) was repeated after finishing the first sweep on flow rate. The measured apparent viscosity was quite different, when compared to the results of the first experiment with the same core. This change on the behavior can be explained by analyzing the drop size distribution of the emulsion as it exits the core, shown in fig. 5. The drop size distribution changes with flow rate (capillary number), approaching a bimodal distribution. One possible explanation is the coalescence of small drops inside the pore space. This phenomenon is still under investigation. However, it is clear the larger drops led to much high apparent viscosity.

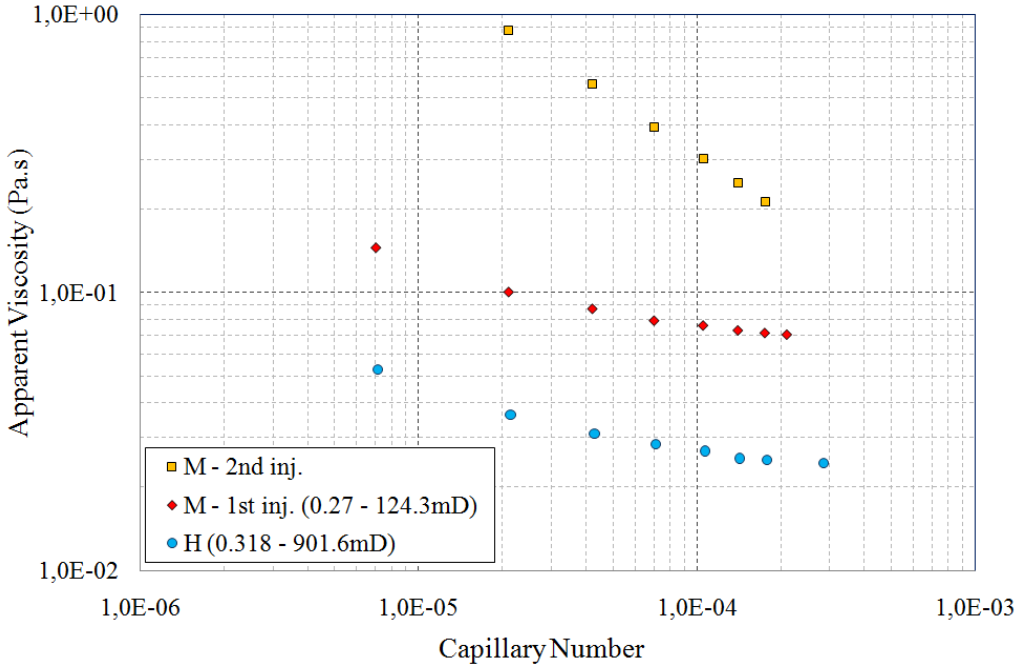

Figure 4. Behavior of the apparent viscosity with the capillary number.

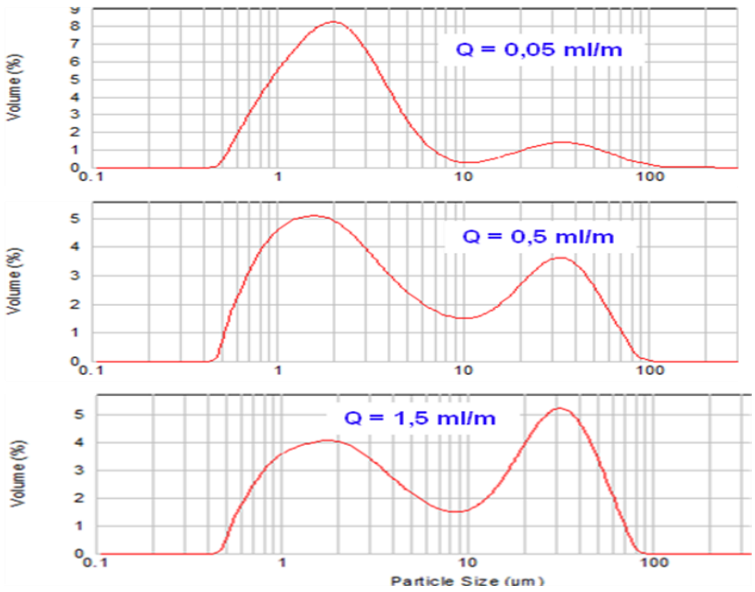

Figure 5. Drop size distribution of the produced emulsion on the 2nd injection through core M.

3. CAPILLARY NETWORK MODEL

The microstructure of a porous medium and the physical characteristic of the solid and the fluids that occupy the pore space determine several macroscopic transport properties of the medium. The prediction of average or macroscopic transport properties from their microscopic origins requires two main steps: (a) a quantitative geometric description of the complex microstructure of the medium, and (b) exact or approximate solutions of the equations of motion that govern the transport phenomena of interest (2002). In recent years, several advances have been made in the construction of realistic representation of porous media. Oren *et al*. (1998 and 2002) and Bakke *et al*. (1996) have developed random network models based on the pore space geometry of the rock of interest. The model is derived either from a direct three-dimensional image of the pore space obtained from micro-CT scanning, or from simulating the geological processes by which the rock was formed.

The network model in this work requires as input a three-dimensional regular or random network comprised of pores connected by throats. Each pore or throat is assigned a total volume, an inscribed radius, and a cross-sectional shape. In this model the pore and throats have a triangular, square or circular cross section. The cross section has the same shape factor (ratio of cross-sectional area to perimeter square) as the real system from which the network is derived. A clay volume is associated with the network. This represents an immobile volume that remains water saturated throughout all displacements. Table 3 lists all parameters that the model reads to construct a network and it is consistent with the network generated by Oren *et al*. (1998 and 2002) and Bakke *et al*. (1996).

A Berea network is used for the modeling studies in this work. A network of pores and throats is generated to represent the topology of the void space of the rock of interest. The Berea network is a cube of volume 27 mm^3 containing 12,349 pores and 26,146 throats, permeability 3.148 mD and porosity 0.18. Figure 6 represent a connectivity of one pore with 19 pores and the position of each one in the space. Figure 7 presents the pore and throat size distribution of the network.

Table 3. Network parameters read by the model

1. Total numbers of pores and throats	10. Index of the throat connecting two pores
2. Length, width, depth of the network	11. Shape factor of each pore and throat
3. Volume of each pore and throat	12. Clay pore volume
4. X,Y, Z coordination of each pore	13. Index of the first and second connecting pore to each throat
5. Inscribed radius of each pore and throat	14. Microporosity volume in each throat
6. Number of connecting pore(s) to each pore	15. Distance between the center of the two connecting pores
7. Index of connecting pore(s) to each pore	16. Length of the first and second pore connecting to each throat
8. Whether each pore is at the inlet	17. Length of each throat
9. Whether each pore is at the outlet	

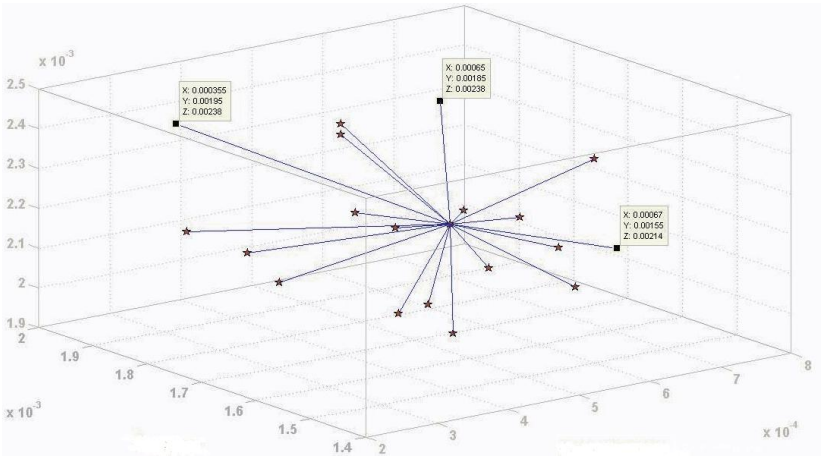

Fig. 7. Representation of the connectivity of one pore in the network.

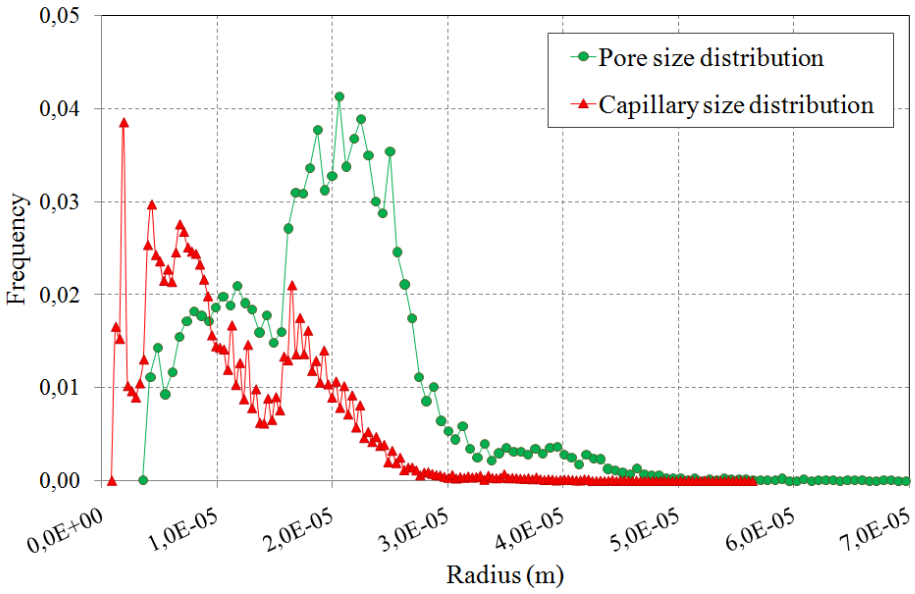

Figure 8. Pore and throat size distributions for the Berea network.

3.4. Modeling the flow of emulsion through porous media

The flow behavior of an emulsion in a porous solid has been evaluated by Devereux (1974a) assuming linear flow relationships. In his first paper, he proposed a model in which the capillarity effects are specifically taken into account describing the flow of stable emulsion in porous solids, yielding a closed form equation for total volume flow vs. time with three experimental parameters: flow constants for each phase and the capillary factor. In his second paper, Devereux (1974b) compared this relation with results of experiments of flow of crude oil-in-water emulsions in porous sandstone. He concluded that the experimental parameters not only were function of saturation and that the previously derived relation provides an accurate description of the results except for high emulsion concentration.

A simplified filtration model was present by Soo *et al.* (1986a and 1986b) describing the flow of stable, dilute emulsions in unconsolidated porous media. In the model, emulsion drops are captured in pores by straining and interception and, thus, reduce the overall permeability. Transient flow is characterized by three parameters: (1) a filter coefficient that controls the sharpness of the emulsion front; (2) a flow-redistribution parameter that dictates the steady-state retention; (3) a flow-restriction parameter that describes the effectiveness of retained drops in reducing permeability.

An extensive review was made by Fischer and Erni (2007) on emulsion drops in external flow fields focusing on recent work involving complex interfaces (which may include the presence of surfactants, particles, surface-active polymers, or solid-like membrane layers). They considered important phenomena in multiphase flow associated with emulsion rheology, including drop coalescence and breakup, surfactant transport, or mechanics of composite interfaces.

As for the review presented, it appears that an accurate model for flow of emulsions in porous media is still not available. We are going to use experimental data from literature of the flow of drops immersed in a continuous liquid phase through a constricted capillary; the microscopic behavior will be considered in the development of a capillary network model to simulate the flow of emulsion in porous media.

3.5. Flow of emulsion through a single constricted capillary

Figure 9 shows the experimental data obtained by Cobos *et al.* (2009). They injected oil-in-water emulsions with different drop size distribution and concentration through capillaries. A scaling factor (defined as the ratio of Poiseuille pressure difference necessary to drive the flow of the continuous phase alone to the one associated with the emulsion flow at the same flow rate) was used to account for the partial pore blocking and it was evaluated for all the emulsions tested in the experiments as a function of the capillary number. The partial pore blocking mechanism related to the presence of large drops on the injected emulsion only occurs if the local capillary number is below a critical value that is a function of the emulsion properties. In this case, it is $Ca_c = 0.008$. If the emulsion properties and process conditions are such that the local capillary number is higher than this value, there is no pore blocking on the emulsion flow through the pore space.

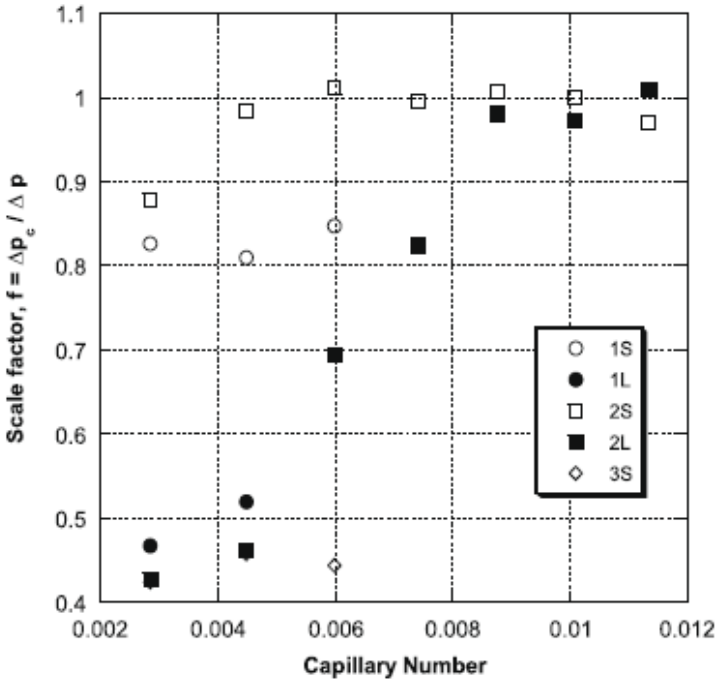

Figure 9. Scale factor used in the definition of capillary mobility for flow of emulsions, from Cobos *et al*. (2009).

The glass capillary tube used by Cobos *et al*. (2009) had a diameter equal to 200 μm and the neck equal to 50 μm. The mean average oil drop in all the emulsions systems used in their experiments was between 9.3 and 51.5 μm. We use the emulsions labeled 1L and 2L in their work, where the minimum ratio of emulsion drop size to capillary neck size (r_e/r_c) was equal to 0.85. Figure 10 shows a snapshot of oil drop deformation as it flows through the throat.

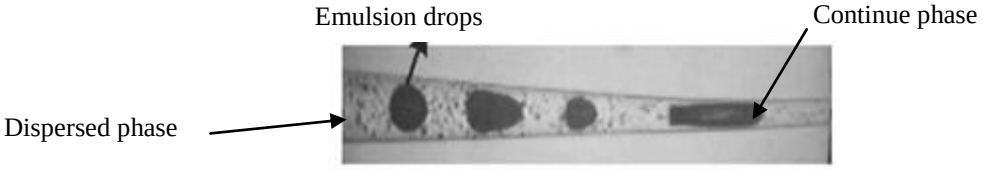

Figure 10. Image of the emulsion flow in a capillary, from Cobos *et al.* (2009).

Based only on the experimental results of Cobos *et al*. (2009), we propose a relationship of the pore blocking factor, *f*, as a function of the drop size to throat size ratio to capillary number. We realize that the available amount of data for the pore level behavior is not enough to derive an accurate function *f*, but our goal is manly to reproduce qualitatively the macroscopic behavior observed in our core flooding experiments. The function for the blocking factor we used was:

$$f_{(re/rc,Ca)} = \left[4 - 5\frac{r_e}{0{,}85r_c} + 4\left(\frac{r_e}{0{,}85r_c} \right)^{1{,}1} \right]^{\left(1-\frac{r_e}{0{,}85r_c}\right)\left(1-\frac{Ca}{Ca_c}\right)} \left[\frac{Ca}{Ca_c} \right]^{\frac{1}{5}\left(1-\frac{0{,}85r_e}{r_c}\right)} \tag{3}$$

Figure 11, shows *f* as a function of r_e/r_c for different capillary numbers. The pore blocking factor can be used to define a local effective viscosity μ_{eff}, defined as:

$$\mu_{eff} = \frac{\mu_{CF}}{f_{(re/rc,Ca)}} \tag{4}$$

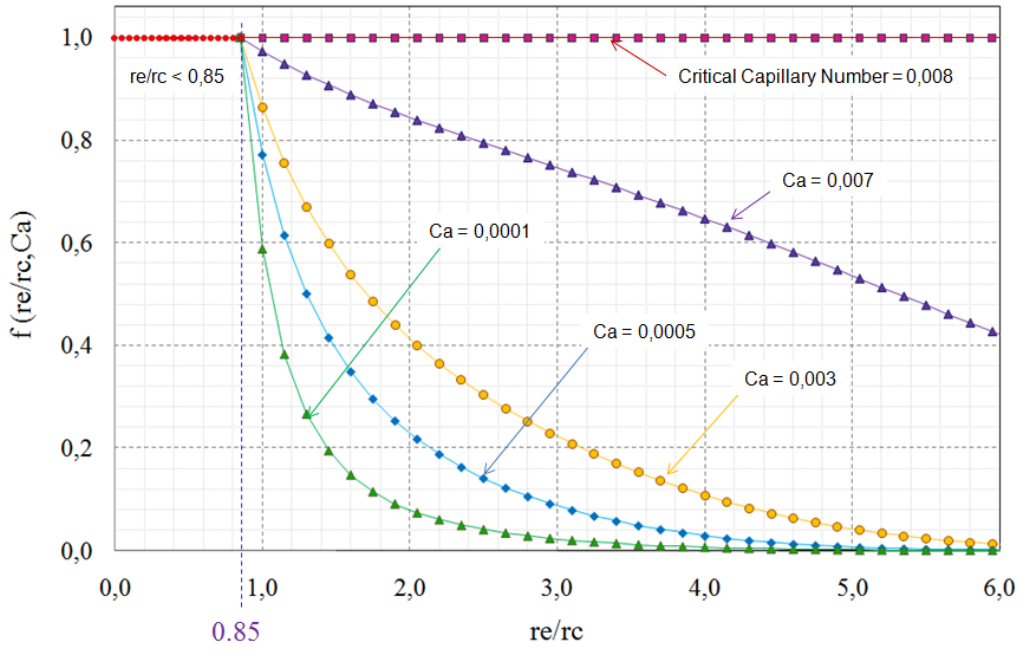

Figure 11. Curves of the factor $f(r_e/r_c)$ at different capillary numbers (Ca_C).

3.6. Numerical simulation

To compare the theoretical predictions with the experiments, we modified the network by changing all lengths rescaled by a factor $\sqrt{K^{\exp}/K^{net}}$, as used by Valvatne *et al*. (2005) to match the experimental data obtained by Cannella *et al.* (1998). The superscripts *exp* and *net* stand for experimental and network, respectively. By construction, the re-scaled network now has the same permeability as the experimental system, but otherwise has the same structure as before.

We assumed the emulsion as a single-phase liquid. Our network model is mainly composed of irregular triangular-shaped pores and throats. To account for non-circular pore shapes, we replace the inscribed radius of the cylinder with an appropriately defined equivalent radius, R_{equ}. We use an empirical approach to define R_{equ} based on the conductance, G, of the pore or throat that is exact for a circular cylinder:

$$R_{equ} = \left(\frac{8G}{\pi}\right)^{1/4} \tag{5}$$

In a network of pores and throats we do not know the pressure drop ΔP of each capillary *a priori*. Hence, to compute the flow and effective viscosities requires an iterative approach. An initial guess is made for the effective viscosity (eq. 1) in each network element. Once each pore and throat has been assigned an effective viscosity and conductance calculated, the relationship between pressure drop and flow rate across each element can be found.

$$Q_i = \frac{G_i}{\mu_{eff}^i}\Delta P_i \tag{6}$$

By using mass conservation in each pore with appropriate inlet and outlet boundary conditions (constant pressure), the pressure field is solved across the entire network solving algebraic system by using the Conjugate Gradient Method. As a result, the pressure drop in each network element is now known, assuming the initial guess for viscosity. Then the effective viscosity of each pore and throat is updated and pressure recomputed. The method is repeated until satisfactory convergence is achieved. The pressure is recomputed if the flow rate in any pore changes by more than 1% between iterations.

3.7. Results

The apparent viscosity predicted by the capillary network model for two networks with permeability values equal to those used in this experiment is show in figure 12. The plot also reproduces the experimental data presented in Figure 4. The predictions for an emulsion with very small drops (r_e = 2 µm) flowing through out a high permeability network (H) show a constant apparent viscosity. In this case, there is no pore blocking, and the flow behavior is very similar to that of the continuous phase.

Predictions with the network with low permeability (M) were obtained with two different emulsions, with r_e = 10 µm and r_e = 20 µm. With the emulsion with r_e = 10 µm, pore blocking is already evident. The predicted apparent viscosity falls with rising capillary number, as in the experiments. The apparent viscosity also rises as the drops size increasing, as expected. This behavior was also observed in the experiments.

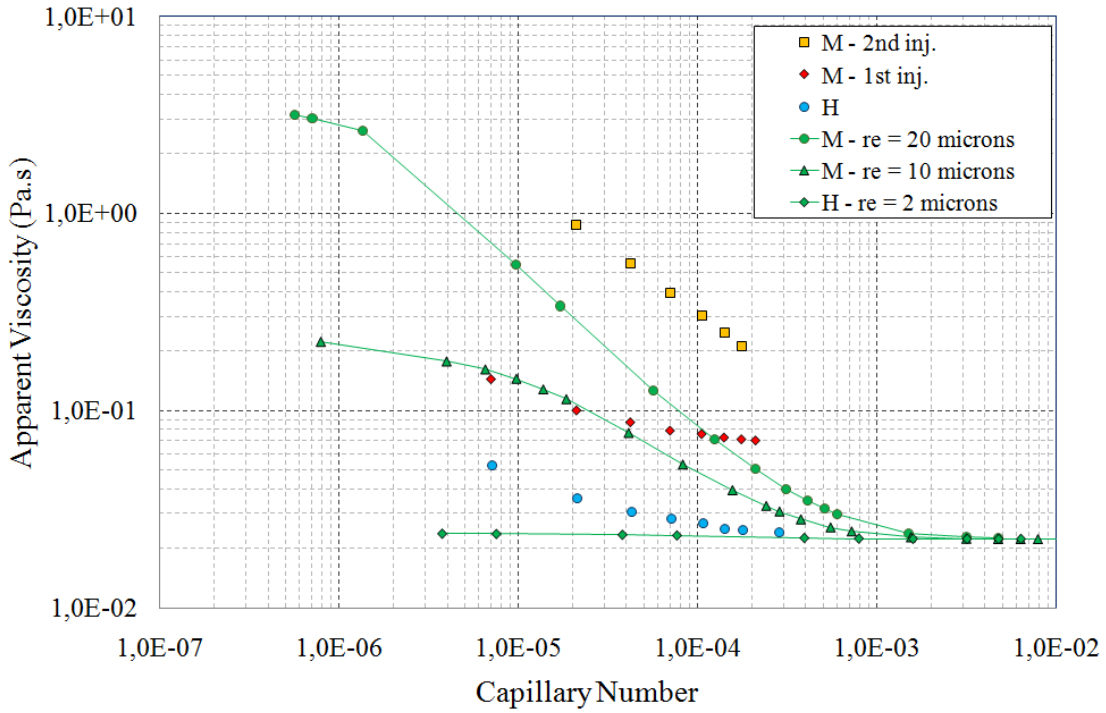

Figure 12. Comparison between the simulation (green line) and experimental data (points).

4. CONCLUSIONS

We presented experimental data to characterize the flow of emulsion through porous media. The results clearly show a partial pore blocking phenomenon, which is a function of the capillary number and the ratio of the size of the dispersed phase drops to the throat radius.

A capillary network model was developed using the experimental data of Cobos *et al.* (2009) for the flow through a constricted capillary. The predictions obtained with the proposed model agree qualitatively with the experiments. The accuracy of the model can be improved by using a better description of the flow through each individual capillary.

5. ACKNOWLEDGEMENT

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