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A CAPILLARY NETWORK MODEL FOR EMULSION/WATER ALTERNATE INJECTION AND ENHANCED OIL RECOVERY

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Abstract*: Emulsions can be used as mobility control agents in different enhanced oil recovery and carbon storage methods in oil reservoirs. The application of this technique, with the correct choice of the injected emulsion characteristics and the determination of optimal operating conditions, requires an adequate understanding of the emulsion flow in porous media. The macroscopic characteristics of the emulsion flow through porous media are directly linked to the two-phase flow at the pore scale. Capillary network models allow the implementation of the drop flow mechanisms in the pore throats and the determination of macroscopic flow parameters. In this work, emulsion flow in porous media is analyzed through an unstructured 3D dynamic network model. The pressure distribution, and consequently the flow rate in each capillary of the network, is determined by mass balance equation in each pore. The effects of the drops of dispersed phase in the flow behavior within each element of the network is described by a flow blocking factor based on experimental results on emulsion flow through single microcapillary tubes with throats. The blocking factor describes the changes in the conductivity of each element and it is a function of the throat geometry, the size and volumetric concentration of the dispersed phase and the local capillary number. The concentration distribution of the dispersed phase along the network is described by a mass transport equation, allowing the study of the filtration process of the drops in the pores and the analysis of the alternate injection of water and emulsion. Time integration in the dynamic model is performed by a semi-implicit method and the non-linear system of equations obtained in each time step is solved by an iterative method. The results illustrate the evolution of the permeability reduction and the effluent concentration of drops as a function of the drops size, injection flow rate, concentration of the injected emulsion and injected volume of emulsion. The analysis of the emulsion/water alternate injection clearly shows the pore blockage by the emulsion drops and the change in the flow pattern after the reinjection of water.*

Keywords: E*mulsion flow, alternate injection, dynamic network model, enhanced oil recovery.*

1. INTRODUCTION

The analysis of the emulsion flow in 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 and drops dynamics.

The prediction of macroscopic transport properties of emulsions can be achieved by developing numerical simulations using capillary network models. It is a powerful method to obtain representative pore-level parameters of the flow. These parameters can be used in the multiphase flow equations to describe the flow behavior in the field scale. Starting from single-phase simulations, it is possible to test the network properly and determine the initial features necessary for an accurate flow description.

Concerning the emulsion droplets effects, there are two basic mechanisms of drops capturing in the porous medium. In the straining, the drops with the same order of magnitude of the throats plug up this narrow passage, diverting the flow to other paths. However, it can be deformed and squeezed through these narrows throats. In the direct interception, small drops are attracted to the pore walls and there is a deposition as a result of hydrodynamic forces and electrical attraction. The deposition rate is affected by the fluids velocity, ionic strength, pH of the continuous phase and oil concentration in the emulsion.

Different works in the literature tried to develop reliable methods to account for the drops retention, considering particle interaction probability or empirical parameters (Rege and Fogler, 1986; Soo and Radke, 1986a, b).

Another physically based can be used to determine the emulsion flow properties, relating the increase of pressure drop due to the presence of emulsion in a capillary tube to viscosity ratio, flow rate and the ratio between drop and capillary diameters (Martinez and Udell, 1990; Khambhratna *et al*, 1998; Bai *et al*, 2000; Cobos *et al*, 2009).

However, it seems that an accurate model is still not available. In this work, we use data obtained from experiments on emulsion flow in a constricted capillary tube. The microscopic behavior of the emulsion drops is considered in the overall flow using 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 to improve the understanding of emulsion flow and its implication in the oil recovery.

2. DYNAMIC NETWORK MODEL

The capillary network consists in void spaces, here called 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 element has a shape factor (cross-sectional area to perimeter squared ratio) and can have scalene triangular, square or circular cross-section. A sketch of a capillary network representing a real sample is illustrated by the Fig. 1.

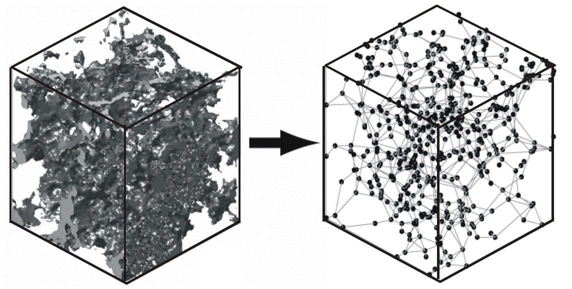

Figure 1. A Berea sandstone sample (a) from Øren *et al*. (1998) and a schematic pore network representing the porous medium (b).

The porous medium is initially saturated with water. 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	Capilares	Poros	Total
Quantidade	26146	12349	38495
Porosidade	4.56	13.74	18.31
Seções quadradas (%)	7.54	4.34	6.51
Seções circulares (%)	1.73	0.17	1.23
Seções triangulares (%)	90.72	95.51	92.26
Raio inscrito mínimo (μm)	0.90	3.62	0.90
Raio inscrito médio (μm)	10.97	19.16	13.60
Raioinscrito máximo (μm)	56.85	73.53	73.53
Número de coordenaçãomédio	-	4.19	-
Número de coordenaçãomáximo	-	19	-
Volume total (mm^3)	-	-	27

2.1. Flow calculation

For single-phase, incompressible flow within tubes with uniform cross section, the Poiseuille's law relates flow rates across each tube to the pressure drop between two nodes. Throat-nodes entry effects and losses were neglected in conductivity computations (Dullien, 1977).

For a single-phase flow, the conductance g is given in terms of the geometric factor, ϵ, and the Mason and Morrow's shape factor, M, by the following expression (Patzek, 1999; Bakke, 2002):

$$g = \epsilon \frac{A}{\mu} M \tag{1}$$

where A stands for the cross sectional area of the element and μ is the fluid viscosity. For a element of arbitrary triangular section, the geometric factor can be considered that one of a equilateral triangle, that is, $\epsilon_t = 3/5$. For squared sections, $\epsilon_q = 0,5623$ and for circular sections, $\epsilon_c = 0{,}5$.

The total fluid conductance between the pore i and j is given by the harmonic mean between the hydraulic conductances of the tube and both connected nodes.

$$\frac{g_{ij}}{l_{ij}} = \left(\frac{l_i}{g_i} + \frac{l_c}{g_c} + \frac{l_j}{g_j}\right)^{-1} \tag{2}$$

It is known that the local imbibition processes are determined by the nodes pressures. Thus, the mass conservation at each node (Eq. 3) gives a set of equations similar to Kirchhoff's equations for resistor networks.

$$\sum_{j=1}^{n} \frac{g_{ij}}{l_{ij}} (p_i - p_j) = 0 \tag{3}$$

The pressure difference 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.

We have done the flow calculations in a dynamic network model, 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). The time step, Δt, is calculated in a way that at most one element in filled at each time step:

$$\Delta t = min\left\{\theta,\ \min_{i=1,\dots,N}\left(\frac{V_i}{Q_i}\right)\right\} \tag{4}$$

Additionally, it is necessary to use the pressure field from the previous time step 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).

2.2. Model for the emulsion flow

We have used experimental data obtained by Cobos, Carvalho and Alvarado (2009), where oil-in-water emulsions were injected in a single capillary tube. Furthermore, a blocking factor (*f*) as a function of the drops-to-tube radius ratio, r_D/r_c, and the capillary number was used to account for the partial or total pore blocking due to the drop-pores 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 ($Ca = 8 \times 10^{-3}$). 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.

Before we can estimate the flow rate when injecting emulsion in the network, it is extremely necessary to study the non-linear behavior related to the factor *f* when considering emulsion flow in constricted capillaries. As the blocking factor is a function of the pressure drop, it is necessary to start from as initial guess for the effective viscosity and to proceed iterative calculations for obtaining the current blocking effect. Thus, we use iterative calculations for obtain the real blocking effect. This makes the problem even more computationally intensive.

In this work, the main goal is to qualitatively reproduce microscopic behavior, since the available amount of data on this approach is not enough to the statement of an accurate blocking function *f*. The shape of the first try for this function can be seen in the Fig. 1.

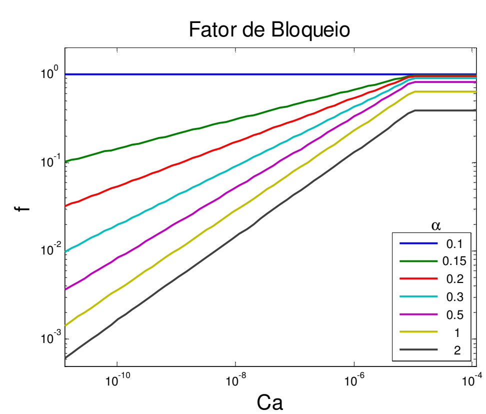

Figure 2. (Color) Blocking factor proposed, f, at different capillary numbers (Ca),considering increasing of the ratio of drops-to-capillary radius.

Notice that the parameter f predicts pore blocking for the capillary number less than a critic value, which is a parameter to be set (in this figure it equals to 10^{-5}). Above the critical value of Ca, inertial effects are considerable and it makes the drops pass through the throat. However, by the instant of passage of a single drop submitted to a flow above the critical value of capillary number, another effect must be considered: the substitution of a less viscous fluid (the continuous phase of the emulsion) by a more viscous fluid (oil). Moreover, even in the case of big drops covering all the cross sectional area of the throat, the local, effective viscosity is less than the oil viscosity, devised to the existence of a thin film of the wetting phase in the crevices of the wall. These whole set of physical properties is represented in the network geometry and in this approach related to the emulsion effective viscosity.

2.3. Drops concentration

Up to now, the effect of the variation in the concentration of dispersed phase drops was not considered in the description of the flow of emulsion within each element of the network. However, in the oil-in-water emulsion injection in a porous medium saturated with water, some of throats of the porous channels are blocked by the drops of the dispersed phase, leading to a variation of the concentration of drops in the network. Furthermore, in oil recovery processes involving emulsion application, the emulsion is injected in the reservoir after a big amount of water, leading to a mixing of the fluid in the pore bodies, increasing the variation of the drops concentration in the porous media. Thus, the modeling of the variation of the dispersed phase concentration is of special importance in the simulation of emulsion injection processes as it occurs in real oil recovery methods.

Considering incompressible flow and applying the mass conservation in a element of volume V_{el}, local drops concentration C_{loc}, the conservation becomes:

$$V_{el}\frac{dC_{loc}}{dt} = Q_{el}(C_{in} - C_{out}) \tag{5}$$

where the differential time step is denote by dt, and the element is supposed to be subjected to the inlet flow rate Q_{el} of a fluid with concentration C_{in}. The effluent concentration is C_{out}. This equation for the local concentration can be easily discretized for the pore throats and the pore bodies.

The concentration profile over the network makes it possible to set an additional equation to turn the final blocking factor in each element, f', a function of the local concentration, the maximum concentration of the injected emulsion, C_{max}, the blocking factor, f, that is a function only of the capillary number and the drop size. The term k_c is an adjustment parameter.

$$f' = 1 + (f-1)\left(\frac{C_{loc}}{C_{max}}\right)^{k_c} \tag{6}$$

It is known that the pressure calculation is responsible for most of the processing time during the simulations. As the local concentration varies slowly with the small time step required for the dynamic model, the pressure distributions can be updated only in the time step in which the drops concentration varies significantly.

2.4 RESULTS

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

The blocking 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 void space constrictions represented in the network by the tubes and can be use as an initial step to the better understanding of how the emulsion drops can do the whished selective pore blockage. Other subject of interest is the influence of the drops concentration in EOR processes.

The figure 3 depicts a typical case of continuous emulsion injected. The overall reduced permeability (permeability over the initial permeability, that is considering only water injection) starts to change after a volume of injected emulsion corresponding to approximately 20% of the network pore volume. The effluent concentration reach the value of the injected concentration after 3 PV injected.

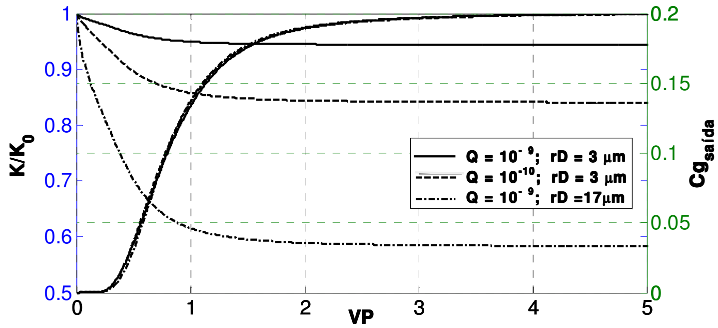

Figure 3. Typical results for continuous emulsion injection

Detailed results are shown in figure 4, where one can see the influence of the drop size and the flow rate, which determines the capillary number. The emulsion drops radius were set in the simulation to three different values, and . The flow rates were varied from and . The transient profile of the drops concentration are to the expectation about emulsion flow in porous media, and the final permeability values are similar to experimental results of Romero *et al.* (2011) and Cobos (2009).

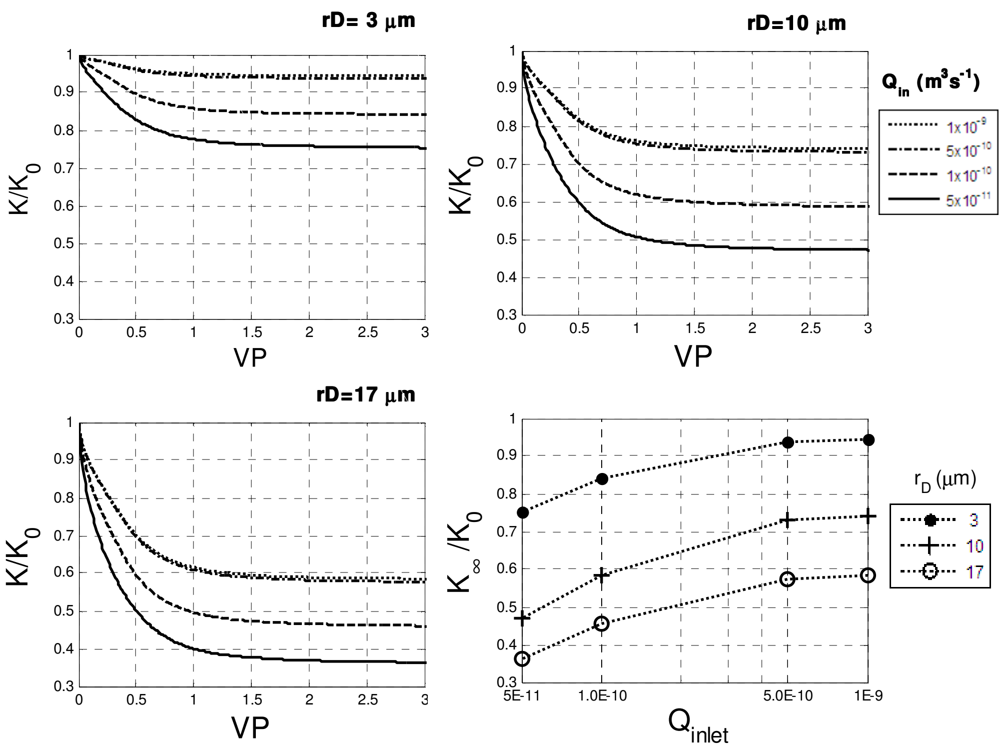

Figure 4. Results for the continuous injection at different flow rates and drops size

Additionally to the possibility of the simulation of emulsion injection in a network saturated with water, it is possible to analyze the influence of the concentration of the injected emulsion in the permeability reduction, as shown in figure 5. In this case the concentration ranged from 2 to 20%.

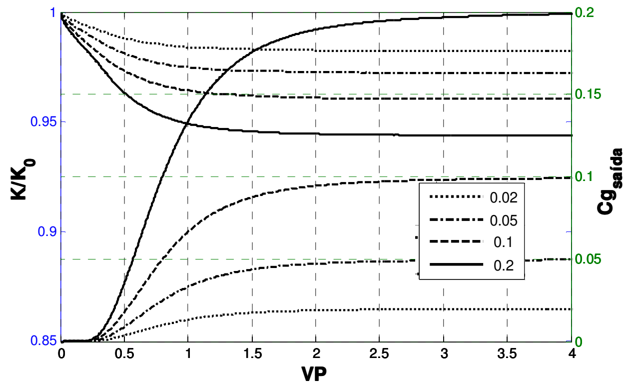

Figure 5. Results for emulsion with different drops concentration

In the simulations of the alternate injection, the volume of injected emulsion was set to 0.1, 0.2, 05 and 0.8 VP. After the emulsion injection, the simulation continued with water injection. It is clear in the figure 6 that the permeability does not reach the initial values, in accordance with the filtration theories.

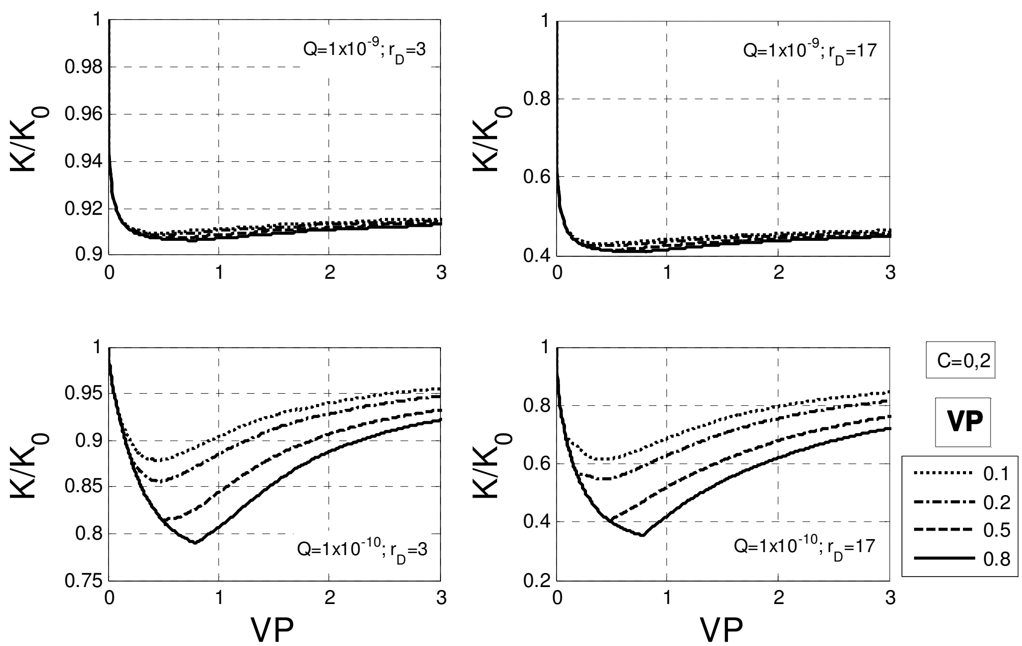

Figure 6. Results for alternate injection with different flow rates

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. The initial results are promising, showing that emulsions can be used in enhanced-oil recovery methods as the objective of blocking preferential paths (the more permeable zones), diverting the flow to the non-swept zones, displacing the oil and increasing the oil recovery factor.

3. ACKNOWLEDGEMENTS

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4. REFERENCES

T Aziz, K. and Settari, A. (1979), *"Petroleum reservoir simulation"*, Applied Science Publisher, London.

Bakke S. and Øren P. E. (1997), "3-D pore-scale modelling of sandstones and flow simulations in the pore networks", *SPE Journal,* 2, 136–149.

Bijeljic, B., Muggeridge, H. and Blunt, M. J. (2004), "Pore-scale modeling of longitudinal dispersion", *Water Resour. Res.*, 40, W11501, doi:10.1029/2004WR003567

Cobos, S., Carvalho, M.S. and Alvarado, V. (2009), "Flow of oil-water emulsion through constricted capillary", *International Journal of multiphase Flow*, 35, 507–515.

Dullien, F.A.L. (1979), *"Porous Media: Fluid transport and pore structure",* 2nd ed., Academic Press, New York.

Fatt, I. (1956), "The network model of porous media, III. Dynamic properties of networks with tube radius distribution", *Petroleum Trans.AIME*, 207, 164–181.

Hui M. H. and Blunt M. J. (2000), "Effects of wettability on three-phase flow in porous media", *Journal of Physical Chemistry B*, 104(16), 3833–3845.

Koplik, J. and Lassester, T.J., 1984, "One and two-phase flow in network models of porous media". *Chemical Engineering Communication*, 26, 285-295.

Martinez, M.J., Udell, K.S. (1990), *Journal of Fluid Mechanics*, 210, 565–591.

McAuliffe, C.D. (1973a), "Crude oil-in-water emulsions to improve fluid flow in a Oil Reservoir", *Journal of Petroleum Technology*, 25, 721–726.

McAuliffe, C.D. (1973b), "Oil-in-water emulsions and their properties in porous media", *Journal of Petroleum Technology*, 25, 727–733.

Øren, P. E., Bakke, S. and Arntzen, O. J. (1998), "Extending predictive capabilities to network models", *SPE Journal*, 3, 324-336.

Ransohoff, T. C., and Radke, C. J. (1988), "Laminar flow of a wetting liquid along the corners of a predominantly gas-occupied noncircular pore", *Journal of Colloid and Interface Science*, 121 (2), 392–401.

Rege, S.D., Fogler, S. (1986), "Network model for straining dominated particle entrapment in porous media", *Chemical Engineering and Science*, vol 42 (7), 1553-1564.

Romero, L., Zirit, J.L., Marín, A., Rojas, F., Mogollón, J.L., Manrique, E., Paz, F. (1996), "Plugging of high permeability : Fractured zones using emulsions", *Symposium on Improved Oil Recovery*, 10, Tulsa, 611–621.

Romero, M. I. (2009), *"Flow of Emulsions in Porous Media: Experiments and Capillary Network Model"*, PhD Thesis, PUC-Rio, Rio de Janeiro.

Sahimi, M. (1994), *"Applications of percolation theory"*, Taylor and Francis, London.

Singh, M and Mohanty, K. (2003), "Dynamic modeling of drainage through three-dimensional porous materials", *Chemical Engineering Science*, 58, 1-18.

Soo, H., Williams, Radke, C.J. (1986a), "A filtration model for the flow of dilute, stable emulsion in porous media - I. Theory", *Chemical Engineering Science*, 41 (2), 263-272.

Soo, H., Williams, M.C.,Radke, C.J. (1986b), "A filtration model for the flow of dilute, stable emulsion in porous media - II. Parameter evaluation and estimation", *Chemical Engineering Science*, 41 (2), 273-281.

Van der Marck, S. C., Matsuura, T., and Glas, J. 1997, "Viscous and capillary pressures during drainage: Network simulations and experiments", *Phyical Review E*, 56, 5675–5687.

Zhou, D., Blunt, M., & Orr Jr., F. M. (1997), "Hydrocarbon drainage along corners of noncircular capillaries", *Journal of Colloids and Interface Science*, 187, 11–21.

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