# OIL-IN-WATER EMULSIONS FLOW THROUGH CONSTRICTED MICRO-CAPILLARIES

**Oswaldo Robles Castillo, oroblesc@yahoo.com**
**Marcio da Silveira Carvalho, msc@puc-rio.br**
Pontificia Universidade Catolica do Rio de Janeiro (PUC-Rio). Department of Mechanical Engineering.
Rua Marques de Sao Vicente 225. Gavea, Rio de Janeiro, RJ, 22453-900. Brasil.

***Abstract.*** *The effect of the oil concentration and the drop size distribution on the characteristics of the flow of an emulsion through a constricted capillary was experimentally analyzed and quantified by the ratio of the pressure drop of the continuous phase flow to the pressure drop of the emulsion flow, at the same flow rate.*
*The results confirm that the ratio between the capillary constriction diameter and the oil drop size is one of the most important parameters for this flow. For large oil drop size emulsions, the deformation of the drop as it flows through the constriction leads to a high extra pressure drop at low capillary numbers. For small oil drop size emulsions, the extra pressure drop is a function of the viscosity ratio and the disperse phase concentration.*

***Keywords****: Emulsion, micro-capillaries, porous media, enhanced oil recovery.*

## 1. INTRODUCTION

The Water injection, as an improved oil recovery method, can occur after production has already been depleted or before primary production from the reservoir has been drained. Remaining oil is swept through the reservoir to production wells by non-uniform displacements fronts, originating entrapped oil in the smallest porous space. Uniform displacement fronts and better reservoir sweep can be achieved by improving the mobility ratio between water and oil, as a result of reducing the viscosity ratio between them.

Polymer solution injection is one of the most used mobility control agent, however, the large volume of polymer needed to increase the viscosity of the injected water turns it into a high-cost oil recovery method. A non high-cost alternative to polymer injection is dispersion injection, in particular emulsions.

The most important advantages of oil in water emulsion injection are: improving the reservoir sweep efficiency by diverting water to non swept pores and the fact of using produced water as injected emulsion. The mobility control is achieved by blocking water paths through the deformation of a dispersed phase drop, whose size is of the same order of magnitude of the pore size or gotten by the agglomeration of small dispersed phase drops. The full understanding of emulsions as mobility control agents and the pore blocking effect may be developed by analyzing different flow regimes of emulsions inside porous media.

McAuliffe (1973) remarked the idea of flooding pore space with dispersed phase drop with a diameter similar to rock pore-throat size, also he studied the oil in water emulsion flow though porous media as blocking agent. Experimental results indicate improvements in reservoir sweep efficiency with lower water-oil-ratio in production wells by using oil in water emulsions instead of water injection.

By inserting tightly Ottawa sand between glass plates, Soo and Radke (1984) developed micro model experiments to prove permeability decreasing due to capture mechanism. This mechanism was analyzed as a filtration process. The variation of the drop size distribution, measured at the inlet and outlet of the porous sample, lets account this mechanism and confirms oil drops captured inside the sample with permeability decrease.

Janssen (2000) studied the flow of immersed drops in liquid continuous phase through capillaries to understand the flow of emulsions through porous media and also remarked the strong influence of the interface between the continuous and dispersed phase in multiphase flow.

Guillen (2007) carried out alternating injection of oil in water emulsions and water in an Arkosic sandstone sample improving significantly the oil recovery factor. Experimental data showed pressure drop increase due to pore throat blocking.

Cobos (2009) remarked that macroscopic properties do not plenty describe the flow behavior of oil in water emulsions at the pore scale. Blockage of porous media throats was modeled by emulsion flow through constricted capillaries. A constricted quartz capillary is used to represent a pore throat that connects two adjacent pore bodies. The effect of the drop size on the pressure drop-flow rate relation was analyzed injecting two different drop size distribution emulsions with the same volumetric dispersed phase fraction, through a 200/50µm constricted capillary. The results indicated that pressure drop fluctuation increased for large drop size emulsions and mobility decreased as emulsion drops flowed through the capillary constriction.

In this work, the analysis of the effect of the drop size on the pressure drop-flow rate relation was extended injecting three different drop size emulsions through two different constricted quartz capillaries.

## 2. EXPERIMENTAL SETUP

The injected oil-in-water emulsions were configured as 5% of dispersed phase and 95% of continuous phase. SHELL Tivela S460 Oil was used as dispersed phase to prepare oil-in-water emulsions, with density and viscosity equal to $\rho$=997.1 kg/m$^3$ and $\mu$= 1.19 Pa.s at 23°C, respectively.

Emulsion continuous phase was formulated as a solution of 85% of glycerin and 15% of distilled water in order to increase its viscosity and to avoid segregation of phases caused by density differences. A surfactant (Sodium Lauryl Sulfate) was used to stabilize the emulsions, to decrease the interfacial tension between the phases and to limit the oil drops coalescence. The surfactant concentration was $6.9\times10^{-3}$ Kg/L, amount equivalent to three times the critical micelle concentration. A magnetic stirrer, FISATOM, Model 754A, was used to mix and homogenize water and surfactant. After the filtration of the homogenized water-surfactant mixture, the glycerin was added and mixed too. The continuous phase density and viscosity were $\rho$=1222.2 kg/m$^3$ and $\mu$= 0.11 Pa.s at 23°C, respectively.

Both phases were emulsified using a six rotational rate mixer, ULTRA TURRAX T-25. The emulsion drop diameter distribution was controlled by the rotation rate of the dispersing tool and the time of mixture; and was measured by using the laser diffraction particle size analyzer, MASTERSIZER (Malvern Instruments, Ltd.), as shown in Tab. 1 and Fig. 1. The interfacial tension of both phases was $\sigma$=4.4mN/m.

Table 1. Geometric properties and emulsifying parameters for the injected emulsions measured at 23°C.

| EMULSION | DROP SIZE | ROTATION RATE [rpm] | TIME OF MIXTURE [s] | d(0.5) [µm] | d(0.9) [µm] |
|---|---|---|---|---|---|
| **SD** | SMALL | 24000 | 60 | 2.370 | 4.805 |
| **MD** | MEDIUM | 6500 | 30 | 9.437 | 48.654 |
| **LD** | LARGE | 6500 | 15 | 20.952 | 109.737 |

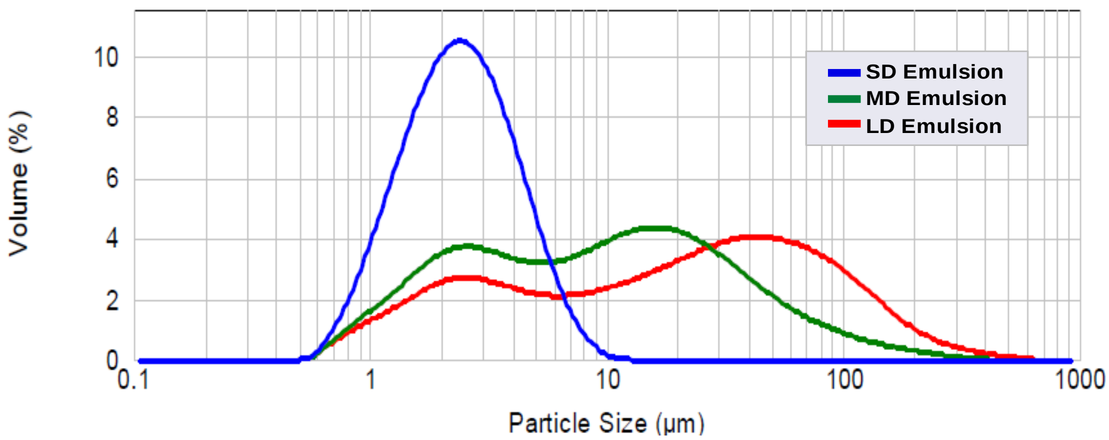


Figure 1. Drop size distribution for the three injected emulsions.

Two different constricted quartz capillaries were used to analyze two different pore geometries. The capillary diameters were 100µm and 200µm, respectively; the constriction diameter and length for both capillaries were 50µm and 80mm, as shown in Fig 2.

Emulsions were poured in 3ml luer lock syringes. Each syringe was mounted in a syringe pump (COLE-PALMER) and connected to the capillary by a three way ball valve, which lets assembly the pressure transducer (VALIDYNE DP15TL) upstream in order to measure the pressure drop along the capillary. The entrapped air from the syringe, valve and connectors was expelled before injecting emulsions at different constant flow rates. Two pressure drop values were acquired per second by using an interface system (VALIDYNE UPC2100).

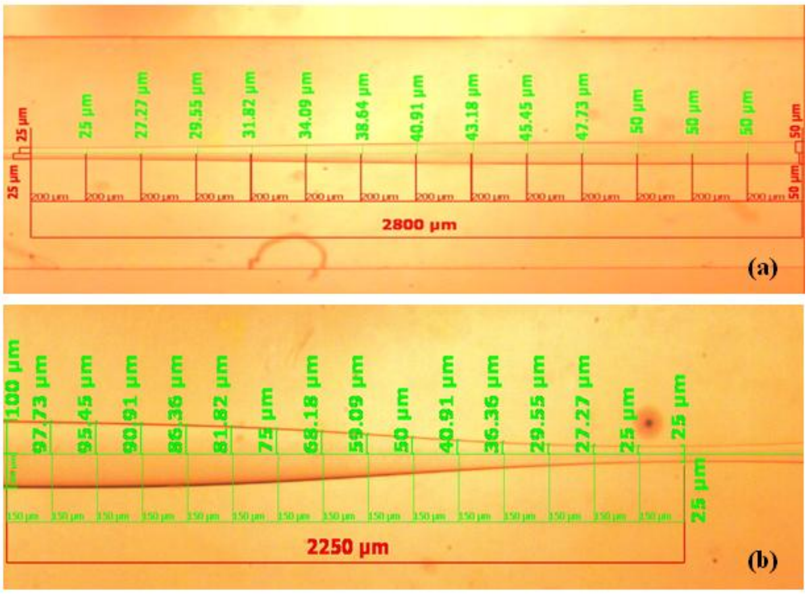


Figure 2. Photographs of the 100/50µm (a) and 200/50µm (b) constricted capillaries.

To visualize the flow of the emulsion through the capillary's constriction, the capillary tube was set on the platform of an inverted CARL ZEISS AXIOVERT 40 MAT microscope with a PixeLINK PL-A662 camera connected to the computer. A sketch of the experimental setup is shown in Fig. 3.

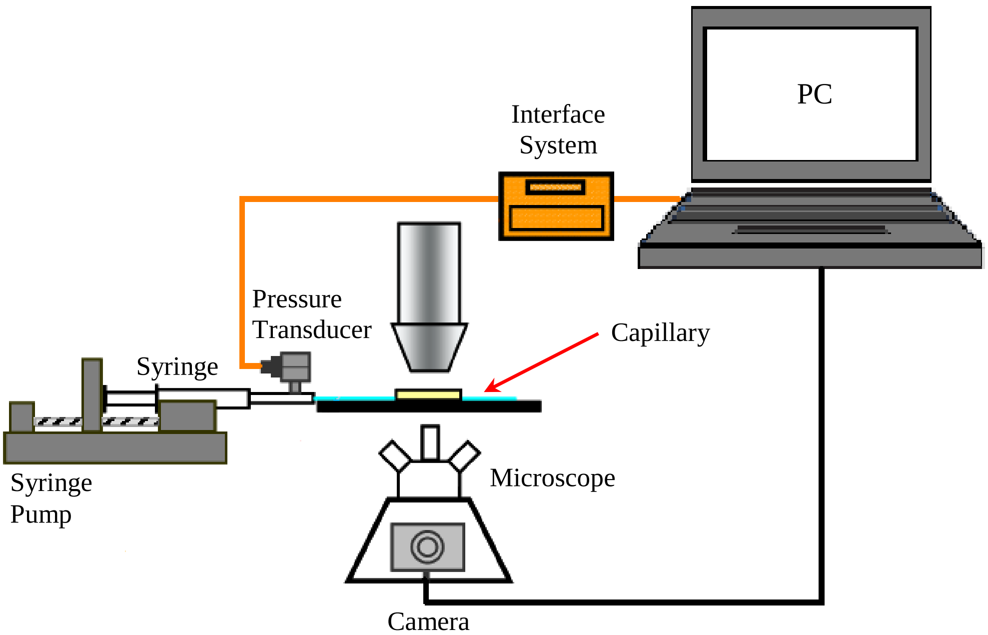


Figure 3. Experimental setup used to measure pressure drop as a function of time.

## 3. RESULTS AND DISCUSSION

Equation (1) expresses the flow of the continuous phase through a constricted capillary, as a function of the continuous phase pressure drop $\Delta P_{CP}$, continuous phase viscosity $\mu_{CP}$, capillary equivalent ratio $\overline{R}$, and capillary length L.

$$Q = \frac{\pi \overline{R}^4}{8\mu_{CP}} \frac{\Delta P_{CP}}{L} \tag{1}$$

The flow of emulsion through a constricted capillary can be expressed as done in Eq. (2) by considering the pressure drop, which is required to push the dispersed phase drops through the capillary constriction, as an extra pressure drop from the one necessary to drive the continuous phase alone.

$$Q = \frac{\pi \bar{R}^4}{8\mu_{CP}} \frac{\Delta P_E}{L} = f \frac{\pi \bar{R}^4}{8\mu_{CP}} \frac{\Delta P_{CP}}{L} \quad (2)$$

The effect of oil drop´s flow was analyzed and quantified through the ratio of the pressure drop of the continuous phase flow to the pressure drop of the emulsion flow, at the same flow rate. This ratio is called Reduction Factor and is defined in Eq. (3).

$$f = \frac{\Delta P_{CP}}{\Delta P_E} \quad (3)$$

Two mechanisms of mobility change for the flow of oil drop through a capillary were studied, the viscous mechanism and the capillary mechanism.

The extra pressure drop is explained by the viscous mechanism as a result of substituting a low viscosity liquid (continuous phase) by a high viscosity liquid (oil) and it is characterized by a decreasing of the reduction factor whereas the ratio of the oil drop radio and the capillary radio and the ratio of the continuous phase viscosity and oil viscosity, both fall. The behavior mentioned before, shows a weak dependence of the flow on the capillary number, which is defined in Eq. (4) as a function of the average velocity $\bar{V}$ , the continuous phase viscosity and the interfacial tension.

On the other hand, the extra pressure drop is defined by the capillary mechanism as a result of the oil drop curvature change due to its deformation as it flows through the constriction. This mechanism is characterized by a decreasing of the reduction factor whereas the curvature change rises at low capillary number and when the capillary number grows the reduction factor approaches 1. There is a strong dependence of the flow on the capillary number and the mobility change takes place only at low capillary numbers.

$$Ca = \frac{\bar{V}\mu_{CP}}{\sigma} \quad (4)$$

The constant flow rates, which were analyzed at 23°C for the continuous phase and emulsions injection through both constricted capillaries, ranged from 0.02ml/h to 0.08ml/h and the pressure drop acquired for each flow rate was fifteen minutes, as shown in Fig. 4 and Fig. 5 for 100/50µm and 200/50µm capillaries, respectively.

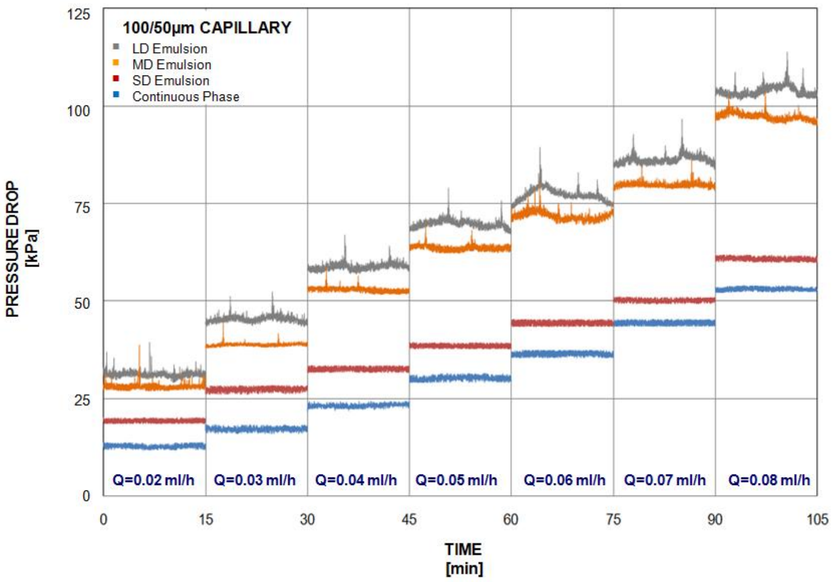


Figure 4. Evolution of the pressure drop as the flow rate varies for the continuous phase and emulsions. Flow rate range: Q = 0.02 - 0.08ml/h. Capillary diameter: 100µm. Constriction diameter: 50µm.

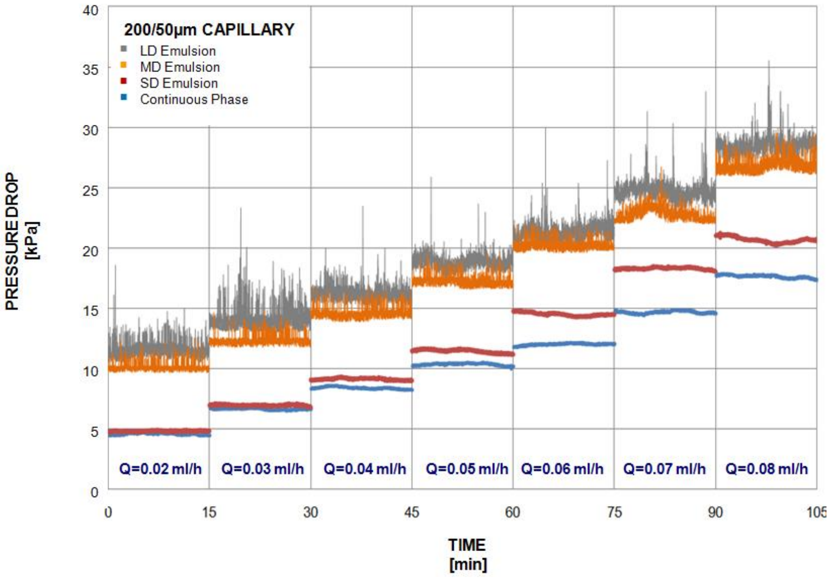


Figure 5. Evolution of the pressure drop as the flow rate varies for the continuous phase and emulsions. Flow rate range: Q = 0.02 - 0.08ml/h. Capillary diameter: 200µm. Constriction diameter: 50µm.

The average pressure drop-flow rate relations in Fig. 6 and Fig. 7 for both capillaries show that large oil drop emulsion and 100/50µm capillary lead to high pressure drop values.

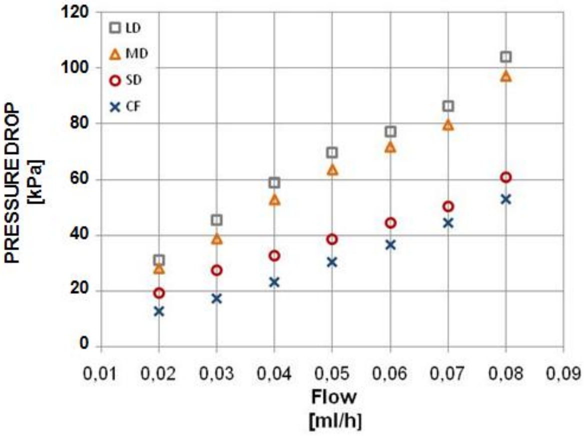


Figure 6. Average pressure drop-flow rate relation for the 100/50µm capillary.

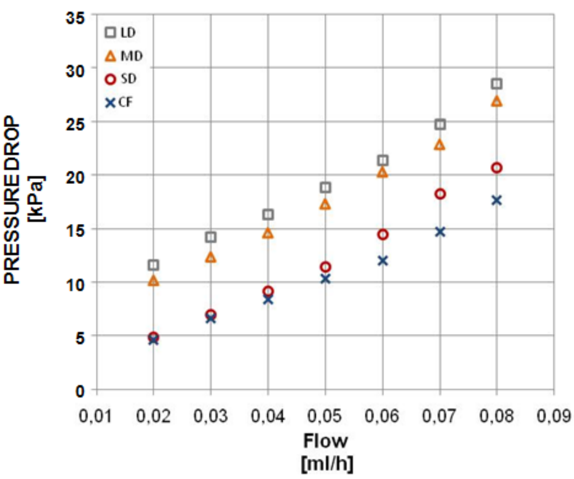


Figure 7. Average pressure drop-flow rate relation for the 200/50µm capillary.

Figure 8 shows the reduction factor *f*, as a function of the capillary number *Ca*, for the three injected emulsions through the 100/50µm capillary. The reduction factor approaches 1 when injecting small drop emulsion and it is less than 1 when injecting emulsion with drop radio larger than or equivalent to the constriction radio. Viscous effect dominates the flow in this pore geometry, remarking a weak dependence on the capillary number.

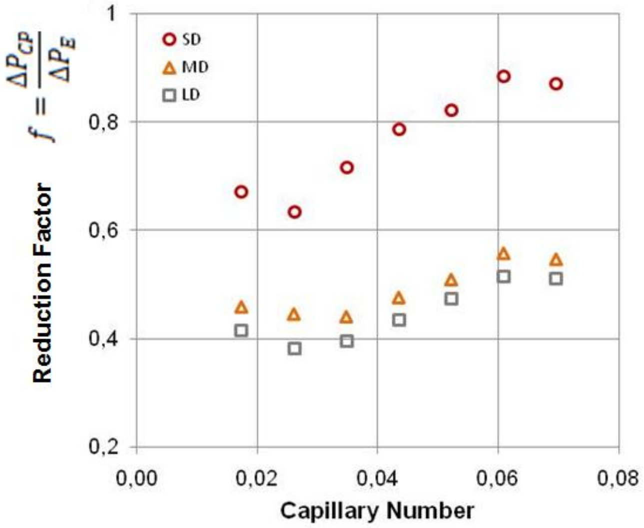


Figure 8. Reduction factor as a function of the Capillary number for the injected emulsions through the 100/50µm capillary.

Figure 9 shows the reduction factor-capillary number relation for the 200/50µm capillary. The effect of the drop size on the reduction factor is as equal as the one observed for the former capillary. Nevertheless, the approach of the reduction factor to 1 as the capillary number increases points out a strong dependence on the capillary number. Capillary effect dominates this flow and pore blocking may take place at low capillary number values.

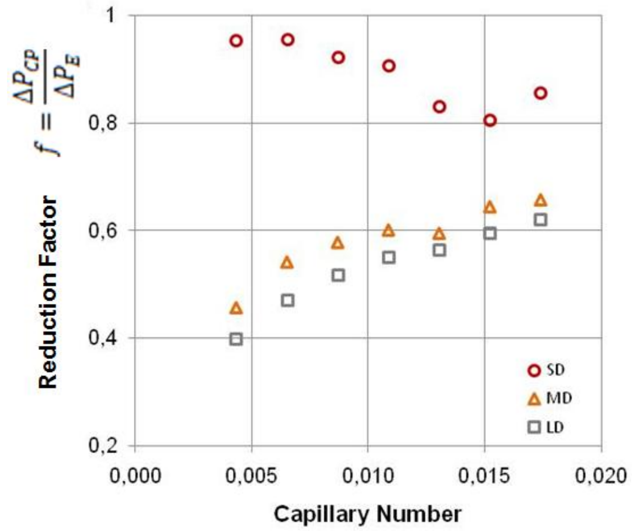


Figure 9. Reduction factor as a function of the Capillary number for the injected emulsions through the 200/50µm capillary.

## 4. CONCLUSIONS

The flow of oil-in-water emulsions through different pore geometries, represented by different constricted quartz capillaries, was characterized by the pressure drop-flow rate relation. The effect of the dispersed phase drop size on the pressure drop was analyzed by comparing the fluctuation of the pressure drop in three different drop size emulsions flow: the first one with drop diameter smaller than the constriction of the capillary, drop diameter of the second one approached to the capillary's constriction and the third one with drop diameter larger than the constriction.

As expected, experimental results indicate that the emulsion flow through the 200/50µm capillary is dominated by capillary effects with a decreasing of local mobility at low capillary number values; it means bellow a critical value.

Further investigation will lead emulsions to be designed to control the mobility of the injected fluid in a desired region of the reservoir.

## 5. ACKNOWLEDGEMENTS

O. Robles was supported by CNPq agency and PUC-Rio through a scholarship. This research was funded by PETROBRAS.

## 6. REFERENCES

Cobos, S., 2009, "Flow of oil-in-water emulsions through a constricted capillary". International Journal of Multiphase Flow, 35, pp. 507-515.

Guillen, R., 2007, "Deslocamento de óleo em um meio poroso através de injeção de emulsões óleo-em-água: Análise de fluxo linear". Master´s thesis. Mechanical Engineering Department, PUC-Rio.

Janssen, P., 2000, "Characterization of oil in water mixtures produced in high-watercuts oil wells". Ph.D Thesis, Delf University of Technology.

McAuliffe, C.D., 1973, "Oil-in-water emulsions and their flow properties in porous media". Journal of Petroleum Technology, 25, pp. 727-733.

Soo, H. and Radke, C., 1984, "The flow mechanism of dilute, stable emulsions in porous media". Ind. Eng. Chem. Fundamentals, 23, pp. 342-347.

## 7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.