Confocal visualization of simultaneous two-phase flow through a 3D microfluidic porous medium

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Abstract: *This work presents a microfluidic 3D model of a porous medium that is employed for pore-scale flow analysis. Confocal microscopy technology is used to enable flow visualization, which allows the study of ganglia dynamics, related to its formation, mobilization and entrapment. The residual oil saturation (SOR) is quantified by image analysis at the end of each displacement process. Results have confirmed the influence of the capillary number (Ca) on the SOR, which modifies the fluid distribution in the porous media. As the capillary number rises, pore-scale displacement efficiency improves leading to lower residual oil saturation.*

Key Words: *3D porous medium; microfluidics ; confocal microscopy*

Introduction: The flow of two immiscible fluids through porous media is important for many technological applications. However, how the two fluids flow in pore-scale is still poorly understood [1]. 2D microfluidic porous media is considerably less connected than a 3D microfluidic porous medium. Therefore, the use of this kind of model is relevant. The visualization of the flow in 3D, at pore-scale resolution, is challenging due to the opacity of the medium. Then, we report the use of confocal microscopy experiments, which provide direct visualization on the simultaneous flow of both a wetting and a non-wetting fluid through a 3D transparent microfluidic porous medium, at pore-scale resolution dynamically and on steady state[2].

Experimental: We prepare the microfluidic 3D porous medium in the lab by sintering glass beads in a square quartz capillary (Figure 1). The glass beads have diameter of 250 µm, the cross-sectional area of the capillary is 9 mm^2, and the length is 2 cm. To avoid the scattering of light from the surfaces of the beads we used formulations composed by Newtonian fluids whose compositions were based on previous work [2]. Then we carefully modified them to match several required properties: a) the refractive indices of the glass beads; b) the viscosity ratio; c) the compatibility of the fluorescent dyes in both fluids and with well-separated emission spectra [3].

a) b) c)

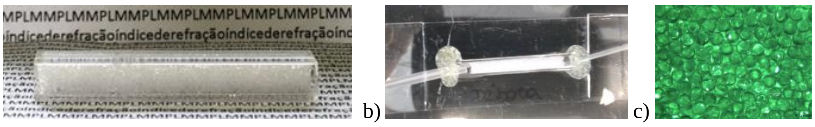


Figure 1 – a) 3D porous medium; b) 3D porous medium connected with tubing; c) microscopic image of the sintered glass beads

The porosity of the devices was calculated by weighting the wet and dry porous medium. The viscosities were evaluated with a rheometer at a constant shear rate of 10 1/s and at 24ºC. The permeability was calculated using Darcy's law. The interfacial tension was measured using a tensiometer Du Noüy ring (Figure 2a). The confocal microscope Leica SP8 was used to image the 3D stacks of the micromodel. To visualize the pore structure in 3D, 168 slices are acquired, each spaced by 2.41 µm along z-direction. These slices were used to reconstruct the 3D structure (Figure 2b).

a) b)

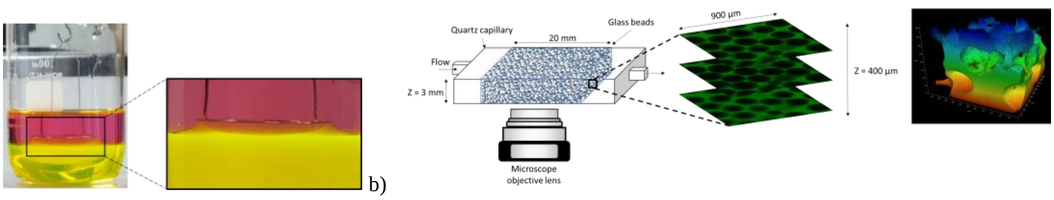


Figure 2 – a) interfacial tension test between the both fluids; b) schematic illustration of the image acquisition of the 3D porous medium

Results and discussion: The porosity of the different media used was between 42 and 46%. The permeability was between 12.63 and 17.87 D. The interfacial tension between the fluids was 17 mN/m at 24ºC, which was very similar with the value observed in the literature for some crude oil and sea water [4].

We characterize the displacement flow based on the effect of capillary number, which represents the ratio of viscous and capillary forces, on the residual oil saturation [5]. These experiments span a range of Ca ≈ 10^{-6} to 10^{-3}. These values were chosen based in the literature, which affirms that it is necessary a Ca of 10^{-3} to mobilize a unique oil droplet trapped in the pore, while values as high as 10^{-2} are necessary to mobilize completely the oil ganglia [6].

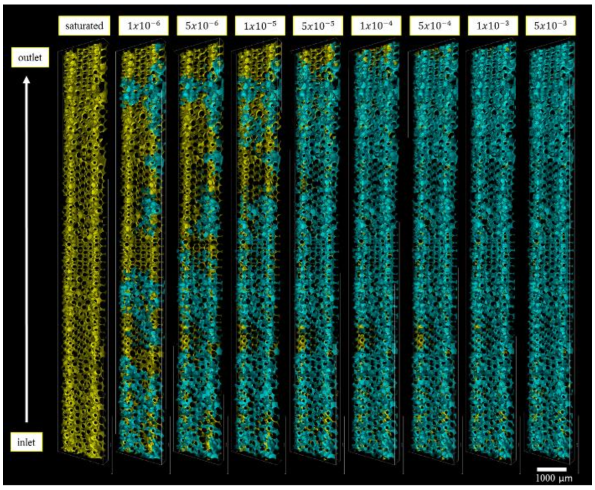
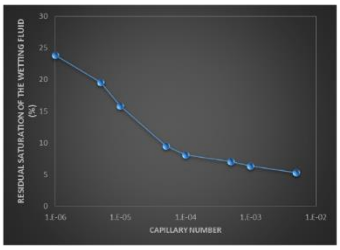


Figure 3 – Confocal images of the steps for the experiments with the 3D microfluidic porous media

After the image acquisition, the images were processed to obtain the volume percentage of each phase. Figure 4 presents a table with the values obtained (Figure 4a) and the effect of capillary number on the residual oil saturation (Figure 4b).

Ca	Q (mL/h)	% residual saturation	% displacement fluid	Total %
1 x10^{-6}	0.02743	**23.82**	17.95	41.8
5 x10^{-6}	0.13715	**19.56**	21.59	41.2
1 x10^{-5}	0.2743	**15.84**	25.45	41.3
5 x10^{-5}	1.37151	**9.54**	31.56	41.1
1 x10^{-4}	2.74303	**8.13**	32.60	40.7
5 x10^{-4}	13.715	**7.07**	33.18	40.3
1 x10^{-3}	27.430	**6.35**	33.44	39.8
5 x10^{-3}	137.151	**5.33**	34.19	39.5

a)



b)

Figure 4 – a) Table with the values of the processed images; b) Desaturation curve

Results have confirmed the strong effect of Ca on SOR, which modifies the fluid distribution in the porous media. This research is very important for the pore-scale analysis. Microfluidics contribute in to a fundamental understanding of the physical mechanisms that govern liquid displacement in the pore scale.

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Acknowledgements: This work was carried out in association with the ongoing Project registered as "Escoamento de dispersões complexas em meios porosos heterogêneos: análise na escala de poro e macroscópica" (PUC-Rio/BG Brasil/Shell Brasil/ANP) - Complex Dispersion Flow Through Porous Media - funded by BG Brasil/Shell Brasil under the ANP R&D levy as "Compromisso de Investimentos com Pesquisa e Desenvolvimento".