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LIQUID-LIQUID DISPLACEMENT FLOWS IN A RADIAL HELE-SHAW CELL

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Abstract. *The Saffman-Taylor instability or viscous fingering is a phenomenon observed when a low viscosity fluid displaces a more viscous one in a porous medium or equivalently in a Hele-Shaw cell, a well-known device consisting of two flat parallel plates separated by a narrow gap forming an effectively two-dimensional channel. The understanding of these interfacial phenomena and the influence of the governing parameters in the formation of patterns is extremely important to improve the efficiency of the displacing processes. This work aims to experimentally study the displacement efficiency of miscible Newtonian fluids in a radial Hele-Shaw cell. We investigated the development of the patterns established by the fluid's interface instability along the displacement. The tests consist of filling the cell with well produced water, which is a crude oil-in-water emulsion. The displacer fluids are represented by (i) aqueous solutions of HCl at pH=2.5, (ii) aqueous solutions of HCl with surfactant at pH=2.5 or (iii) flushing fluid. After a one volume displacement, another volume of produced water is injected. For all pairs of fluids and flow rates explored, it was observed a mixture between the fluids due to miscible effects. Viscous fingerings were only observed when produced water displaces the flushing fluid, indicating that the stability of the interface depends on the viscosity ratio.*

Keywords: *Displacement flow, Enhanced oil recovery, Porous media, Hele-Shaw cell, Viscous fingering*

1. INTRODUCTION

Complex pattern formation is frequently found in nature and industrial processes. Applications include bacterial colony growth, displacement of crude oil in reservoirs, drilling fluid invasion through porous media, hydrology, formation of crystals and snowflakes, among others. These phenomena occur in completely different scientific fields nevertheless are modeled by similar mathematical principles (Xu, 1998).

The Saffman-Taylor instability or viscous Fingering is a phenomenon that occurs when a less viscous fluid displaces a more viscous fluid confined in a geometry with a narrow gap, such as a Hele-Shaw cell. Small instabilities may arise at the fluid interface, driven by viscosity ratio, density or surface tension, which leads to the formation of fingers (ramifications). Viscous fingering with miscible fluid in a porous medium or a Hele-Shaw cell have been extensively studied by several authors (Habermann, 1960; Heller, 1966; Mahaffey *et al.*, 1966; Paterson, 1985; Lajeunesse *et al.*, 2001; Bischofberger *et al.*, 2014; Videbæk and Nagel, 2019; Keable *et al.*, 2022).

Displacement flow in a confined geometry is a common process studied in several different manners due to their countless applications, for example, EOR and IOR (Orr and Taber, 1984; Blunt *et al.*, 1993; Sydansk and Romero-Zeron, 2011), printing devices (Taylor, 1963), carbon sequestration (Cinar *et al.*, 2007), biomedical applications (Howell *et al.*,

2000; Huh *et al.*, 2007), food processing (Fryer *et al.*, 2006; Wiklund *et al.*, 2010) and biofilms applications (Cogan and Keener, 2005; Burfoot *et al.*, 2009).

Enhanced oil recovery (EOR) methods have become more attractive after rising oil prices, specially because approximately 60-70% of the oil in place cannot be produced by conventional methods (Fink, 2021). The use of Hele-Shaw cells for flow analysis in porous media allows a detailed observation of the oil displacement process. It enables the analysis of the oil sweep by water and the identification of preferential paths in fluid-fluid displacement systems.

Heller (1966) studied the stability of miscible fluid displacement on the macroscopic scale in a porous medium. He reported that finger growth between miscible fluids are driven by hydrodynamic dispersion. Keable *et al.* (2022) observed a significant delay in the onset of the fingering instability. Initially, the step interface between displaced and displacer fluid spreads faster by diffusion/dispersion than the growth of fingers. They presumed that the initial stable zone is larger in radial flows subject to velocity-dependent dispersion due to increasing velocities near the inlet.

The purpose of this research is to explore the displacement of well produced water in a radial Hele-Shaw cell aiming to contribute to improvements in the understanding of fluid displacement in porous media such as petroleum reservoirs and EOR scenarios. In general terms, the displacement efficiency was measured relative to one cell volume pumped for three pairs of fluids at two different flow rates.

2. MATERIALS AND METHODS

2.1 Fluids

Produced water, aqueous solution of HCl at pH = 2.5, aqueous solution of HCl with 1% of surfactant at pH = 2.5 and flushing fluid were the fluids chosen for the tests. All of them are miscible and Newtonian.

The viscosity and density of the working fluids were measured in a viscometer and a pycnometer, respectively. Table 1 shows the results obtained.

Table 1. Fluids properties at 20°C

Fluid	ρ [Kg/m ³]	μ [Pa.s]
Well produced water	998.2	1.024
Aqueous solution of HCl at pH=2.5	998.3	1.012
Aqueous solution of HCl with surfactant at pH=2.5	998.6	1.077
Flushing fluid	960.7	26.112

It is worth mentioning that produced water is a stable fluid for a short time. Therefore, the samples were prepared on each day of testing and their duration was limited by the samples' stability. These were interrupted when the phase separation began to be observed.

To evaluate the influence of gravitational effects, the density ratio was defined as shown in Eq. 1.

$$\rho^* = \frac{\rho_{\text{displacer}}}{\rho_{\text{displaced}}} \quad (1)$$

And to investigate the influence of viscous effects, the viscosity ratio was defined as shown in Eq. 2.

$$\mu^* = \frac{\mu_{\text{displacer}}}{\mu_{\text{displaced}}} \quad (2)$$

2.2 Experimental setup

The experimental setup of Fig. 1 was used to study the displacement of Newtonian fluids in reservoirs. The setup consists of a radial Hele-Shaw cell, a digital camera, supports for the equipments, reservoirs for the working and cleaning fluids, fluid transfer vessels and a helical pump with frequency inverter.

The digital camera (model EOS 40D by Canon) is utilized to visualize the interface's time evolution along the displacement. It has Full-HD resolution with 29.97 frames per second (*fps*) and EFS 18-55 mm lens. Due to the dimensions of the experimental setup, a support was made to enable the necessary focal length and allow a fixed positioning of the camera in relation to the Hele-Shaw cell.

Fluid transfer vessel is a sealed cylinder-piston system with an upper and lower threaded cap. Initially, the piston is positioned in the lower part of the cylinder and the upper part is filled with the fluid of interest. Thereby, water is injected by the inlet bottom of the bottle and the piston moves, displacing the fluid of interest. For each fluid used, a calibration of the pump must be made as a function of the pressure drop variation.

The radial Hele-Shaw cell consists of two flat glass discs with 600 mm diameter and 10 mm thickness to prevent bending, see Fig. 2(a). The lower disk has a hole in the central region with 4 mm diameter. A three-way valve is

connected to this hole for independent injection of the fluids to minimize the mixing length. The discs are separated by spacers of rigid material, which creates a constant gap of $340\mu\text{m}$ between them. This causes a limitation in the cell because it generates regions that make the outlet of fluids unfeasible. For this reason, there will always be a small amount of stagnant fluid adjacent to the spacers and an influence of the outlet region on the flow profile. Figure 2(b) shows the inlet region, one of the outlet regions and one of the spacers. In addition, light emitting diodes (LED) and a butter paper were positioned under the disc to provide uniform illumination.

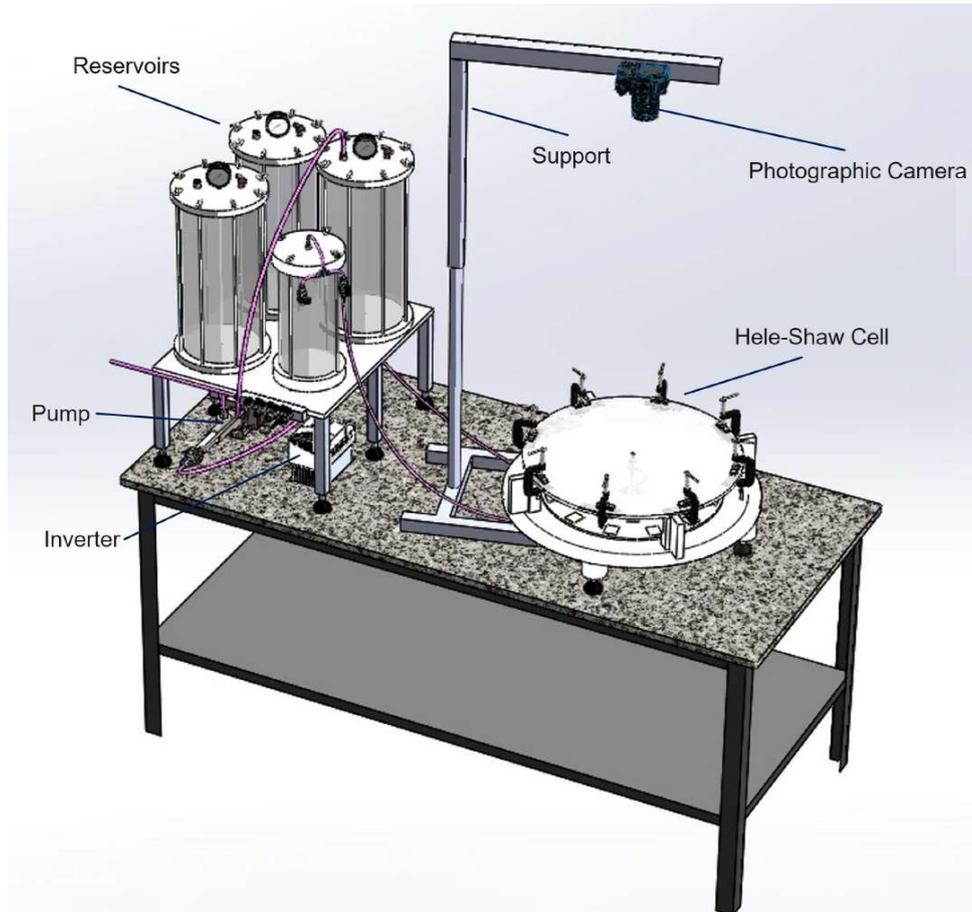


Figure 1. Schematic drawing of experimental bench.

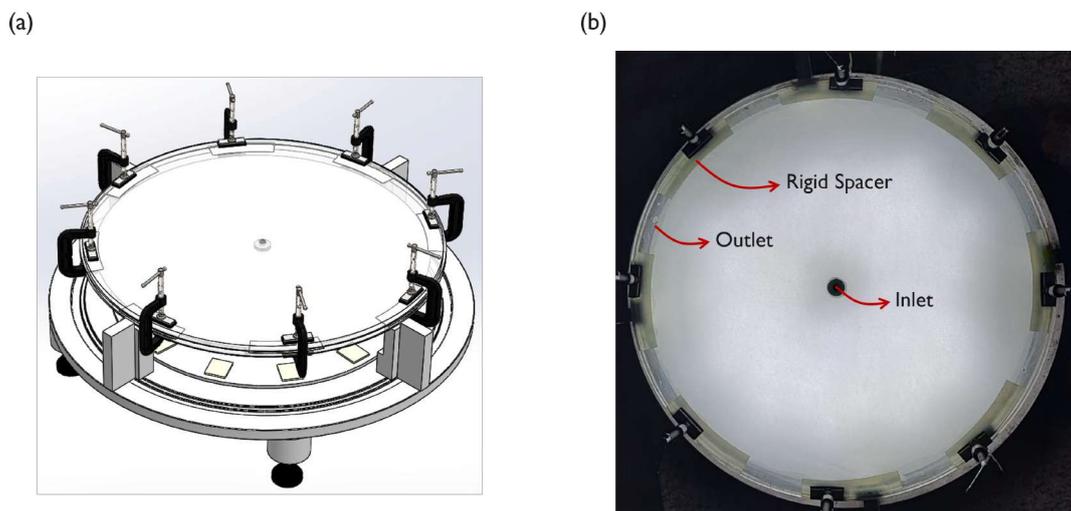


Figure 2. Detailed setup of the test section: (a) schematic drawing and (b) photograph.

2.3 Experimental procedure

Initially, it is crucial to clean all the reservoirs, the tubes and the Hele-Shaw cell for testing. The cleaning of all components is extremely important to remove residues and other impurities. Secondly, the fluid transfer vessels are filled with the working fluids, one of the reservoirs is filled with cleaning fluid and the other with water to operate the fluid transfer vessel, as well as the entire hydraulic circuit before the test section. Another preliminary stage is the pump calibration that allows us to investigate two different flow rates, one being the double of the other. This procedure provides the definition of the runtime of each test by the ratio between the useful volume of the cell and the pumping flow rate.

Subsequently, the Hele-Shaw cell and camera are positioned and leveled. The LED lights are turned on and the laboratory lights are turned off. The cell is filled with the produced water carefully to avoid unwanted disturbances such as small air bubbles. Afterwards, the video recording is started and the pump is turned on at the flow rate of interest to start the experiment. In this first stage, the displacer fluid is represented by aqueous solution of HCl (with or without surfactant) or flushing fluid. After one volume of the cell is pumped, the displacement is interrupted and one volume of the produced water is injected into the cell again.

2.4 Image post processing

After the experimental test, the displacement efficiency is calculated. For this purpose, it was developed a methodology for the digital image processing in the software Fiji based on the color histogram from the obtained images. Through differences in the fluid's colour spectrum, it is possible to identify the interface.

First, the frames are extracted from the video and cropped in order to isolate the section of interest. As the first image of the video contains only produced water in the cell, it is possible to store the illumination characteristics of the photo sequence. This is important because by subtracting this image from the subsequent ones, shadows and lights that difficult the interface recognition are removed. Due to the fluid miscibility, camera and illumination limitations, it was necessary to perform an adjustment of the histograms through "Histogram Matching" method (Coltuc *et al.*, 2006). After the background subtraction, an image segmentation was performed using the technique called bi-modal thresholding (or thresholding) by the Otsu method (Otsu, 1979). This maximizes a measure of variance between the two modes of the histogram to binarize the image. Therefore, the displaced fluid is represented in white and the displaced fluid in black.

Figure 3 shows the post-processed image for the case involving produced water and aqueous solution of HCl.

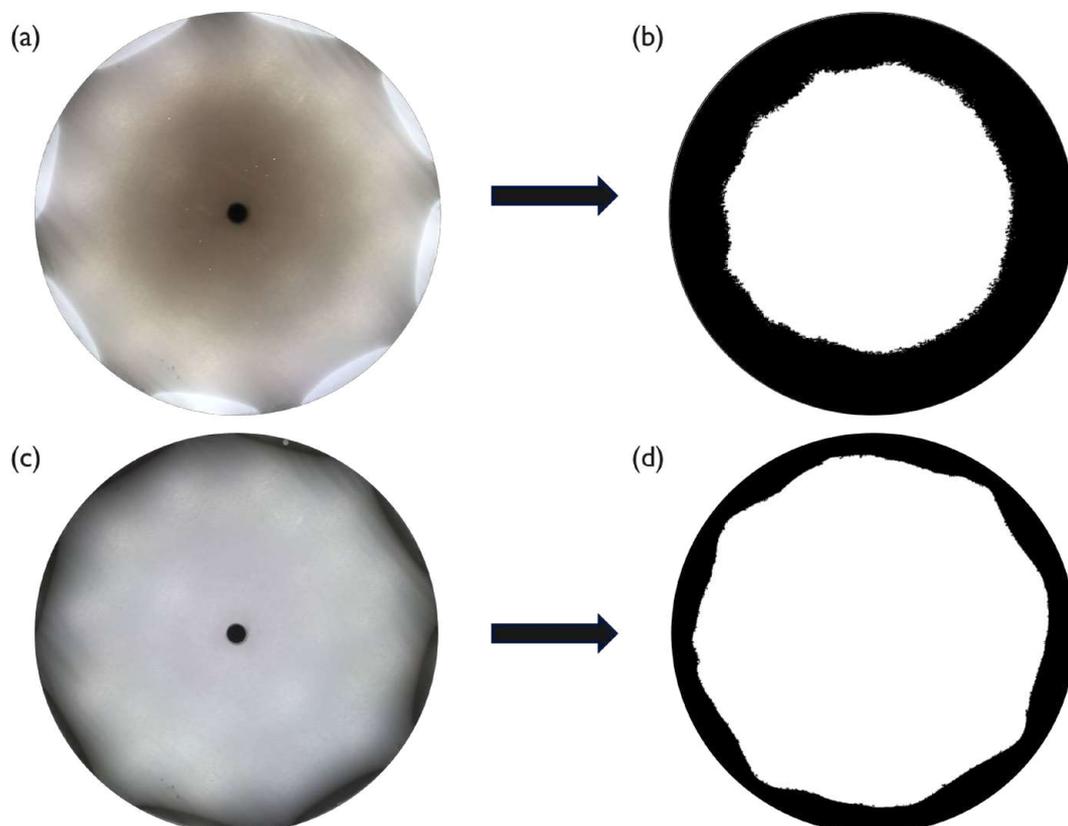


Figure 3. Produced water being displaced by aqueous solution of HCl at a flow rate Q : (a) original image and (b) post-processed image. Produced water displacing the previous mixture: (c) original image and (d) post-processed image.

The displacement efficiency is calculated as the ratio between the sum of the frequency of pixels referring to the displacer fluid (white) and the total sum of pixels filling the cell (white + black) as shown in equation 3.

$$E_f = \frac{\sum f_{\text{displacer}}}{\sum f_{\text{total}}} \quad (3)$$

3. EXPERIMENTAL RESULTS

Tables 2 and 3 show the obtained results from the experiments involving produced water displacements in a radial Hele-Shaw cell. For each scenario, at least 2 tests were performed to ensure repeatability.

Table 2. Summary of the obtained results for step 1.

Step 1				
Displaced Fluid	Displacer Fluid	Q ₁ [m ³ /s]	Ef ₁ [%]	μ* ₁ [Pa.s]
Well produced water	Aqueous solution of HCl at pH=2.5	1.67E-06	50.06	0.99
		3.28E-06	54.50	
	Aqueous solution of HCl with surfactant at pH=2.5	1.23E-06	59.30	1.05
		3.00E-06	55.14	
	Flushing fluid	1.20E-06	62.57	25.50
		2.58E-06	53.14	

Table 3. Summary of the obtained results for step 2.

Step 2				
Displaced Fluid	Displacer Fluid	Q ₂ [m ³ /s]	Ef ₂ [%]	μ* ₂ [Pa.s]
Aqueous solution of HCl at pH=2.5	Well produced water	1.31E-06	82.49	1.01
		3.37E-06	57.97	
Aqueous solution of HCl with surfactant at pH=2.5		1.65E-06	75.65	0.95
		3.37E-06	76.04	
Flushing fluid		1.29E-06	12.57	0.04
		2.96E-06	10.43	

Figure 4 illustrates an example of the images obtained with aqueous HCl solutions. Produced water displacing an aqueous solution of HCl in the lower explored flow rate is presented in Fig. 4(a). About the second step of this scenario, the photograph of produced water displacing the previous mixture is presented in Fig. 4(b). The same flow pattern was observed in all cases involving aqueous solution of HCl, see Figures 5, 6 and 7.

When surfactant is absent, it was observed that the displacement efficiency increases with viscosity ratio. The opposite behavior was observed by reducing the interfacial tension. It was not possible to establish a trend about the influence of flow rate in the scenarios with acid solutions. It is worth mentioning that such cases present density ratio almost equal to 1, which minimizes the influence of gravitational effects.

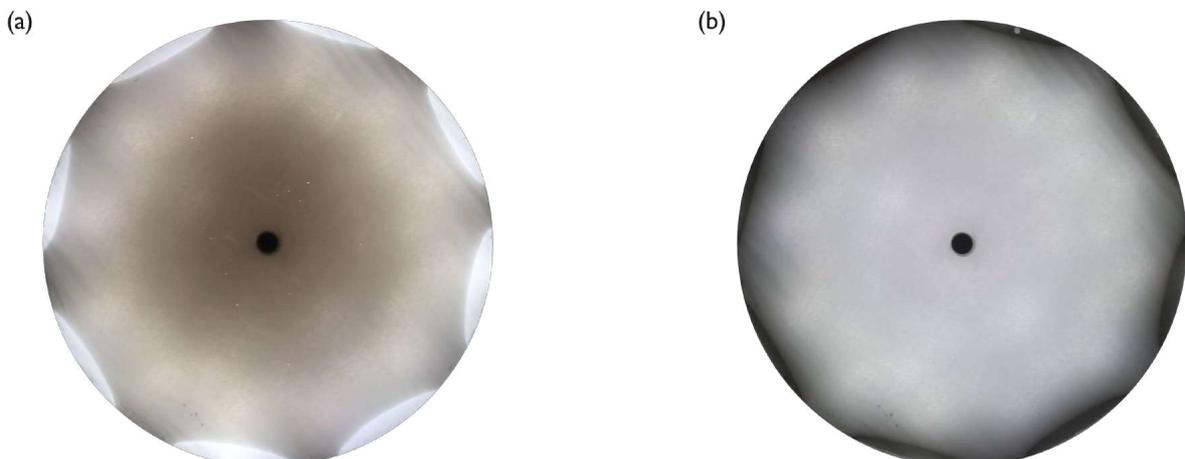


Figure 4. (a) Produced water being displaced by aqueous solution of HCl at a flow rate Q and (b) produced water displacing the previous mixture.

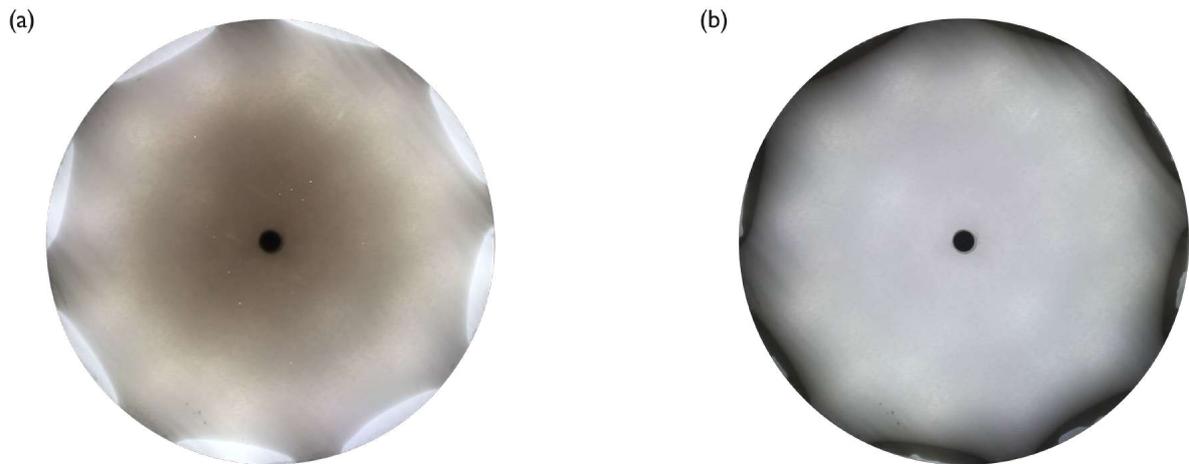


Figure 5. (a) Produced water being displaced by aqueous solution of HCl at a flow rate $2Q$ and (b) produced water displacing the previous mixture.

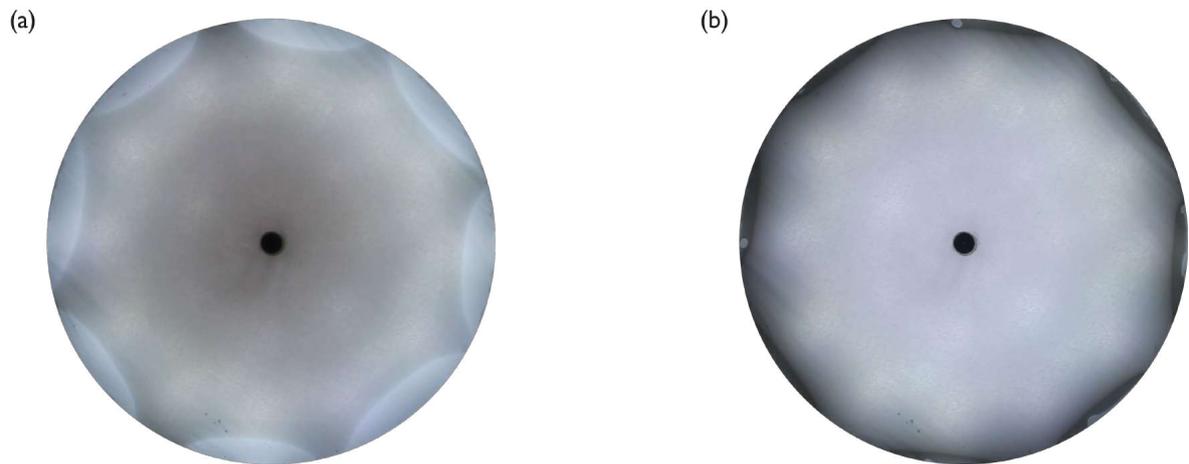


Figure 6. (a) Produced water being displaced by aqueous solution of HCl with surfactant at a flow rate Q and (b) produced water displacing the previous mixture.

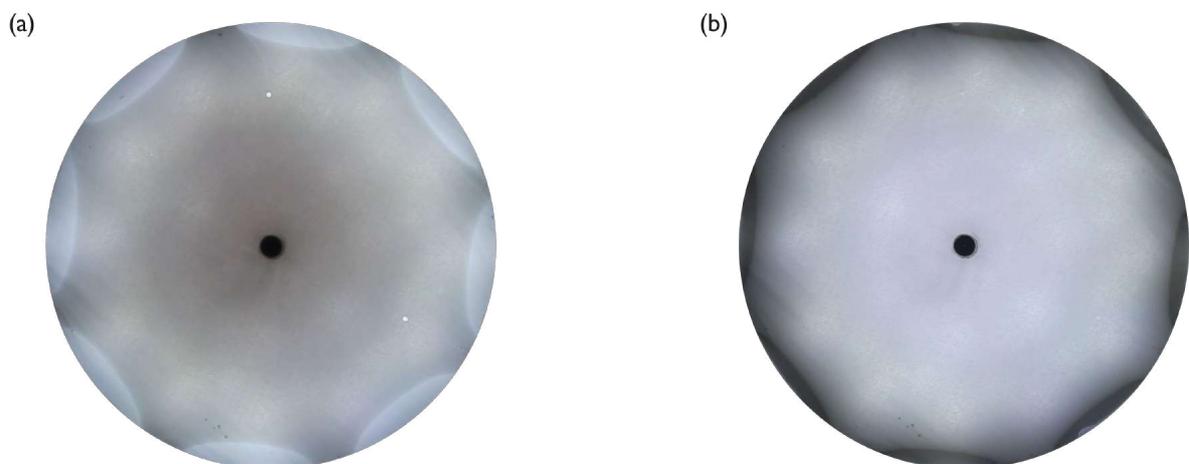


Figure 7. (a) Produced water being displaced by aqueous solution of HCl with surfactant at a flow rate $2Q$ and (b) produced water displacing the previous mixture.

Tests involving the flushing fluid revealed a different displacement pattern, see Fig. 8. This case was realized considering the lowest flow rate, where Fig. 8(a) represents produced water being displaced by the flushing fluid and Fig. 8(b) shows produced water displacing the previous mixture. Such figure contains a description of the regions with retained

(trapped) fluid, displaced fluid and mixing region. Furthermore, Figure 9 presents results of the same pairs of fluids being displaced at highest flow rate.

The scenarios involving flushing fluid are strongly influenced by the viscosity ratio. Flushing fluid displacing produced water presents $\mu_1^* = 25.50$, which minimizes the formation of viscous fingering, leading to a higher displacement efficiency. The opposite case is characterized by $\mu_2^* = 0.04$ and lots of ramifications at the fluid interface. As the fluids are miscible, there is a larger mixing region, which decreases the displacement efficiency. Moreover, this latter case is the one with the worst displacement efficiency among the investigated scenarios. In addition, it was observed that the displacement efficiency decreases with the flow rate increases.

Displacements involving flushing fluid may also have been influenced by gravitational effects, since they present $\rho_1^* = 0.96$ and $\rho_2^* = 1.04$. Due to the difference between the produced water and viscous mattress densities, which cause recirculations in the theta-z plane (around the r direction), introduce an uncertainty in our method of determining efficiency. This effect tends to be more important leaving larger and higher flow rates.

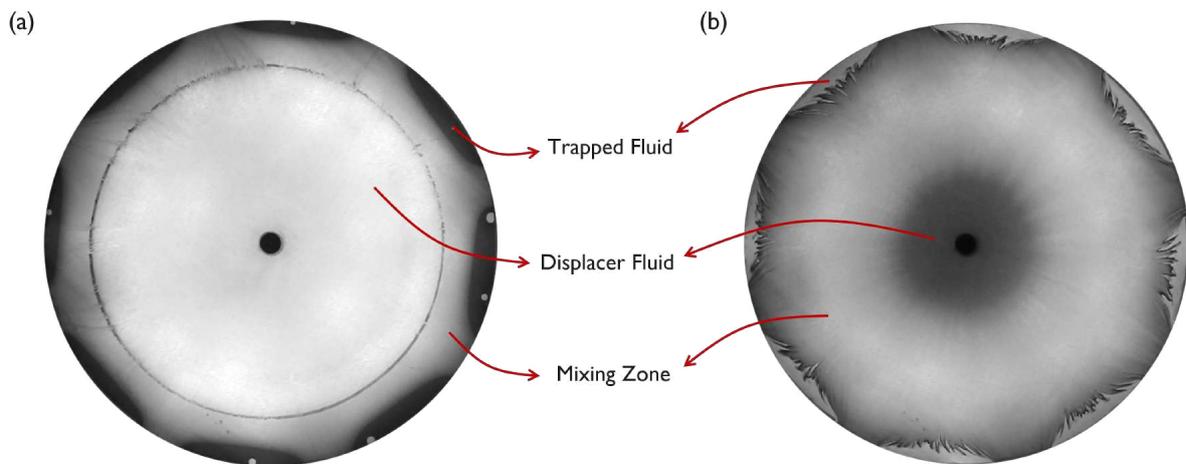


Figure 8. (a) Produced water being displaced by flushing fluid at a flow rate Q and (b) produced water displacing the previous mixture.

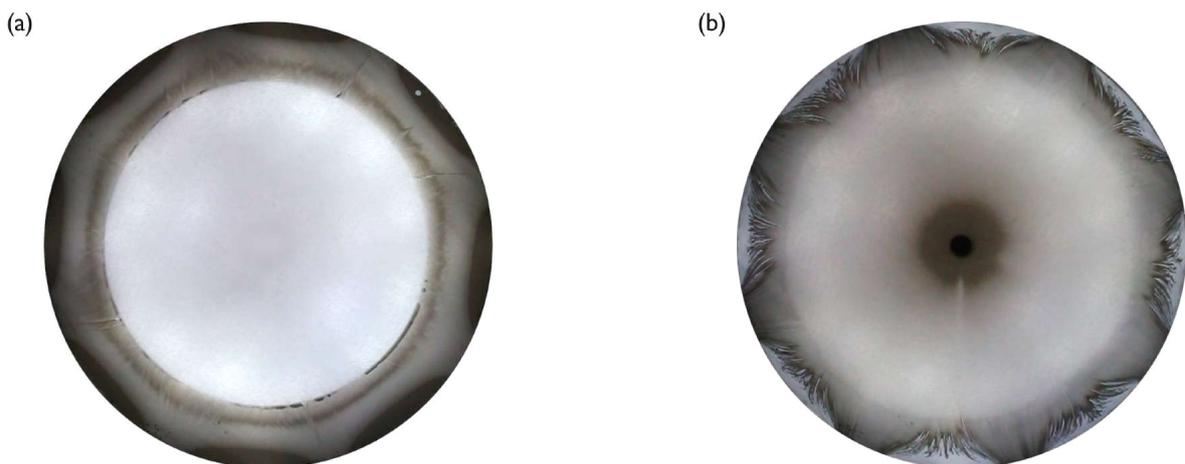


Figure 9. (a) Produced water being displaced by flushing fluid at a flow rate $2Q$ and (b) produced water displacing the previous mixture

4. CONCLUSION

In this work an experimental study of miscible displacement flows in a radial Hele-Shaw cell was performed. The tests consist of displacing well produced water by aqueous solutions of HCl at pH=2.5 (with or without surfactant) or flushing fluid. After a one volume displacement, another volume of produced water was injected. For all pairs of fluids, two flow rates was explored.

The formation of viscous fingers occurred only when the produced water displaces the flushing fluid ($\mu^* = 0.04$) and for all the cases was observed a mixing region. It is important to mention that for the unstable scenarios, the viscous fingers

were narrowing along the flow. It is presumed that the diffusion/dispersion has a strong influence on the aforementioned effects. The displacement efficiency increases with the viscosity ratio in absence of surfactant and the opposite behavior was seen when this substance is present. For the flushing fluid when the viscosity ratio decreases the displacement efficiency decreases drastically, leading for the worst case among the investigate scenarios (10% - 12% efficiency).

The results obtained collaborate in the understanding of the phenomena involved in displacements in porous media. However, it should be noted that it is only possible to make a qualitative comparison between the results because the Hele-Shaw cell is a model system that assumes several hypotheses and simplifications.

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6. REFERENCES

- Bischofberger, I., Ramachandran, R. and Nagel, S., 2014. "Fingering versus stability in the limit of zero interfacial tension". *Nature Communications*, Vol. 5, No. 1. doi:10.1038/ncomms6265.
- Blunt, M., Fayers, F. and Orr, F.M., 1993. "Carbon dioxide in enhanced oil recovery". *Energy Conversion and Management*, Vol. 34, No. 9-11, pp. 1197–1204. doi:10.1016/0196-8904(93)90069-m.
- Burfoot, D., Middleton, K. and Holah, J., 2009. "Removal of biofilms and stubborn soil by pressure washing". *Trends in Food Science & Technology*, Vol. 20, pp. S45–S47. doi:10.1016/j.tifs.2009.01.042.
- Cinar, Y., Riaz, A. and Tchelepi, H.A., 2007. "Experimental study of CO₂ injection into saline formations". doi: 10.2118/110628-ms.
- Cogan, N.G. and Keener, J.P., 2005. "Channel formation in gels". *SIAM Journal on Applied Mathematics*, Vol. 65, No. 6, pp. 1839–1854. doi:10.1137/040605515.
- Coltuc, D., Bolon, P. and Chassery, J.M., 2006. "Exact histogram specification". *IEEE Transactions on Image Processing*, Vol. 15, No. 5, pp. 1143–1152. doi:10.1109/TIP.2005.864170.
- Fink, J., 2021. *Petroleum Engineer's Guide to Oil Field Chemicals and Fluids*. Elsevier Science & Technology. ISBN 9780323854382.
- Fryer, P.J., Christian, G.K. and Liu, W., 2006. "How hygiene happens: physics and chemistry of cleaning". *International Journal of Dairy Technology*, Vol. 59, No. 2, pp. 76–84. doi:10.1111/j.1471-0307.2006.00249.x.
- Habermann, B., 1960. "The efficiency of miscible displacement as a function of mobility ratio". *Transactions of the AIME*, Vol. 219, No. 01, pp. 264–272. doi:10.2118/1540-g.
- Heller, J.P., 1966. "Onset of instability patterns between miscible fluids in porous media". *Journal of Applied Physics*, Vol. 37, No. 4, pp. 1566–1579. doi:10.1063/1.1708569.
- Howell, P.D., Waters, S.L. and Grotberg, J.B., 2000. "The propagation of a liquid bolus along a liquid-lined flexible tube". *Journal of Fluid Mechanics*, Vol. 406, pp. 309–335. doi:10.1017/S0022112099007417.
- Huh, D., Fujioka, H., Tung, Y.C., Futai, N., Paine, R., Grotberg, J.B. and Takayama, S., 2007. "Acoustically detectable cellular-level lung injury induced by fluid mechanical stresses in microfluidic airway systems". *Proceedings of the National Academy of Sciences*, Vol. 104, No. 48, pp. 18886–18891. doi:10.1073/pnas.0610868104.
- Keable, D., Jones, A., Krevor, S., Muggerridge, A. and Jackson, S., 2022. "The effect of viscosity ratio and pecllet number on miscible viscous fingering in a hele-shaw cell: A combined numerical and experimental study". *Transport in Porous Media*. doi:10.1007/s11242-022-01778-4.
- Lajeunesse, E., Martin, J., Rakotomalala, N., Salin, D. and Yortsos, Y.C., 2001. "The threshold of the instability in miscible displacements in a hele-shaw cell at high rates". *Physics of Fluids*, Vol. 13, No. 3, pp. 799–801. doi: 10.1063/1.1347959.
- Mahaffey, J., Rutherford, W. and Matthews, C., 1966. "Sweep efficiency by miscible displacement in a five-spot". *Society of Petroleum Engineers Journal*, Vol. 6, No. 01, pp. 73–80. doi:10.2118/1233-pa.
- Orr, F.M. and Taber, J.J., 1984. "Use of carbon dioxide in enhanced oil recovery". *Science*, Vol. 224, No. 4649, pp. 563–569. doi:10.1126/science.224.4649.563.
- Otsu, N., 1979. "A threshold selection method from gray-level histograms". *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 9, No. 1, pp. 62–66. doi:10.1109/tsmc.1979.4310076.
- Paterson, L., 1985. "Fingering with miscible fluids in a hele shaw cell". *Physics of Fluids*, Vol. 28, No. 1, pp. 26–30. doi:10.1063/1.865195.
- Sydansk, R.D. and Romero-Zeron, L., 2011. *Reservoir Conformance Improvement*. Society of Petroleum Engineers.
- Taylor, G.I., 1963. "Cavitation of a viscous fluid in narrow passages". *Journal of Fluid Mechanics*, Vol. 16, No. 4, pp. 595–619. doi:10.1017/S0022112063001002.
- Videbæk, T. and Nagel, S., 2019. "Diffusion-driven transition between two regimes of viscous fingering". *Physical Review Fluids*, Vol. 4, No. 3. doi:10.1103/physrevfluids.4.033902.

Wiklund, J., Stading, M. and Trägårdh, C., 2010. “Monitoring liquid displacement of model and industrial fluids in pipes by in-line ultrasonic rheometry”. *Journal of Food Engineering*, Vol. 99, No. 3, pp. 330–337. doi: 10.1016/j.jfoodeng.2010.03.011.

Xu, J.J., 1998. *Interfacial Wave Theory of Pattern Formation*. Springer Berlin Heidelberg. doi:10.1007/978-3-642-80435-9.

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