ANALYZING MULTI-PHASE FLOW IN 3D PRINTED MICRO-MODELS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Analyzing Multi-Phase Flow in 3D Printed Micro-Models

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In a world where energy demands are increasing and resources are depleting, gaining better insights into fluid saturation distributions and transport mechanisms within hydrocarbon reservoirs at the pore scale will be critical to maximizing future production of oil and gas globally. This research project is based on understanding multi-phase flow in porous media, which will be done through analyzing the flow in transparent micro-models fabricated using 3D printing tools. These micro-models will facilitate the direct visualization of drainage and imbibition within porous media through the use of image visualization techniques which include the use of thin-section micrographs, micro CT orthoslices, and conventional digital photographs. An open-source toolkit, written in MATLAB language, will be used to generate the micro-models, and through this research, we hope to demonstrate the toolkit's capabilities. Orthoslices of scanned rocks (Berea sandstone) will be cropped and segmented and then used to generate watertight 3D meshes of micro-models which will then be 3D printed. The availability of such a toolset will act as a major enabler for community research in porous media transport phenomena, allowing experimental pore networks to be generated rapidly and cost-effectively using readily available additive manufacturing technologies.

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CHAPTER I

INTRODUCTION

The world's energy demands are growing by the day, and it is our responsibility as petroleum engineers to meet this demand in an efficient and cost-effective manner. Advancements in reservoir characterization techniques are set to play an integral role in meeting future energy requirements, facilitating the optimized utilization of existing hydrocarbon reserves and future discoveries. For example, advancements in micron-scale volume imaging (i.e. via x-ray micro computed tomography) over the past decade mean that it is now possible to routinely investigate rock samples at the pore--scale, as well as to observe the fluid flow processes therein. Such advancements provide petroleum engineers with an improved understanding over immiscible displacement processes in real rock pore systems, enabling them to make better informed decisions over which recovery technique to select for a given reservoir setting. Indeed, as focus within the oil and gas business shifts towards evermore geologically challenging settings, gaining improved insights into fluid saturation distributions and transport mechanisms at this fundamental scale will be critical to maximizing future production globally.

Whilst x-ray tomography represents the de facto tool for investigating the pore structure and pore scale fluid flow behavior or real rocks, significant insights into the producibility of reservoirs can be gained using fabricated proxy pore networks (micromodels), modelled around real pore systems. Indeed, previous work has demonstrated such models can be rapidly prototyped using in-house developed software and consumer-grade 3D printer (Seers and Alyafei, 2018). More recently, 3D printed rock models have found practical application in petroleum engineering and rock mechanics (e.g. Kong et al., 2018a; Kong et al., 2018b). Building upon the aforementioned studies, in this proposal we will consider the potential of utilizing additive manufacturing (3D printing) as an alternative to conventional micro-model fabrication techniques. The development of relatively low-cost consumer-grade 3D printing systems such as fused depositional modelling, Stereo Lithography or selective laser sintering based systems (Wong and Hernandez, 2012) now enables physical representations of pore networks to be routinely fabricated from X-ray micro-tomographic (μCT) images of rocks using polymer (plastic) based materials (e.g. Ishutov et al., 2015; Jiang et al., 2016; Ju et al., 2014). With the advent of light transmissible 3D printable materials (e.g. Willis et al., 2012), flow experiments conducted using these 3D printed physical models can now be captured using widely available optical imaging techniques (i.e. standalone digital cameras and trinocular microscopes). Our plan is to observe fluid flow in these 3D printed micro-models using such optical imaging techniques. Herein, 3D printed micro-models will facilitate the direct visualization of drainage and imbibition and analysis of viscous fingering and capillary trapping effects within quasi-2D porous media, generated from a range of imaging modalities, which include thin section micrographs, micro-CT orthoslices and conventional digital photographs. An open source toolkit, written in MATLAB, will be used to generate the micro-models, and through this research we hope to demonstrate the toolkit's capabilities. Orthoslices of scanned rocks (Berea sandstone) will be cropped and segmented (binarized) and then used to generate watertight 3D meshes of micro-models. The availability of such a toolset will act as a major enabler for community research in porous media transport phenomena, allowing experimental quasi-2D pore networks to be generated rapidly and cost effectively using available additive manufacturing technologies (Seers and Alyafei, 2018).

Video footage of fluid imbibition and drainage experiments conducted across quasi-2D pore networks will be used to understand fluid distributions and displacement mechanisms within an equivalent 3D porous media. Analysis will be linked to investigations on viscous fingering and capillary trapping. Contrary to state-of the-art dynamic micro-CT core flood experiments, which require advanced equipment, the micro-model studies proposed by this research can be undertaken routinely within a lab-based setting with a relativey simple experimental setup.

CHAPTER II

OBJECTIVES AND SIGNIFICANCE

Finding new oil reservoirs is becoming progressively more challenging, with a trend towards discoveries within geologically more complex settings. In these marginal plays, it has become increasingly important to determine if extraction is economically feasible in a given reservoir. It is a common place to base this appraisal upon the study of fluid flow and saturation distributions at the pore scale (i.e. via pore-scale computational fluid dynamics simulations using micro CT volume images: digital rock physics), reducing the need for expensive lab-based measurements. The results of this project may provide major contributions within this context, with the 3D printed transparent micro-models developed by this study providing routine tools to study pore scale transport phenomena, complimenting simulation based digital rock physics workflows. The viability of the 3D printed micro-modelling technique is proven through several literature works (Ishutov et al., 2015; Davoudinejad et al., 2019; Ardila et al., 2019; Kong et al., 2019).

The 3D printing toolkit that will be utilized in this project will also act as an enabler for community research for the study of transport in a porous media. The open source toolkit presented here offers a more accessible and adaptive approach to micro-model fabrication, when compared to conventional etched/molded equivalents, which require highly specialized manufacturing facilities. It will allow experimental pore networks to be generated quickly in a cost-efficient fashion, using readily available manufacturing technologies (Seers and Alyafei, 2018). Drainage and imbibition are important flow processes in reservoirs, and this work will help users to understand such processes by visualizing in 3D printed porous micro-models. Furthermore, special focus will be given to investigating viscous fingering and capillary trapping effects in these systems. This research is impactful, as it will aid the development of an innovative, cost-effect and efficient technique to characterize flow in porous media. The flow visualization and analysis that users will conduct will enable them to develop a better understanding of fluid flow in porous media within reservoirs. In terms of benefit towards the industry, the petroleum industry in Qatar still faces significant amount of uncertainties associated in the upstream sector. Potential findings of this project can correlate directly in understanding how to improve oil recovery in Qatar and worldwide.

CHAPTER III

METHODS

The project is based on a qualitative study and will comprise of experimental and analytical work. The research entails thorough the investigation of viscous fingering, capillary trapping, drainage and imbibition processes within representative 3D printed micro-models to understand transport phenomena within equivalent reservoirs. The project is broken down into the following parts:

i. Image Processing

2D images were sourced from a wide range of imaging modalities, such as digital photography and X-ray CT orthoslices. This project analyzes a mixture of homogenous and heterogenous rock pore systems. The images to be created into the micro-models were developed on the Adobe Illustrator software. The shape tool was used to create the simple shapes needed for the homogenous models (**Figure 1**). As for the heterogenous models, actual microscopic images of rock pore-networks were illustrated (**Figure 2**). These images were segmented into binary images, and filters were applied to remove noise from the image data. For segmentation of input data into binary images, both gradient thresholding and watershed transform based methods are provided, with cropping tools made available to enable user specified regions of interest to be used for micro-model generation. The presented toolkit can also be used to clean artifacts attributable to image segmentation, such as holes, isolated pixels and small pixel clusters, prior to micro-model generation.

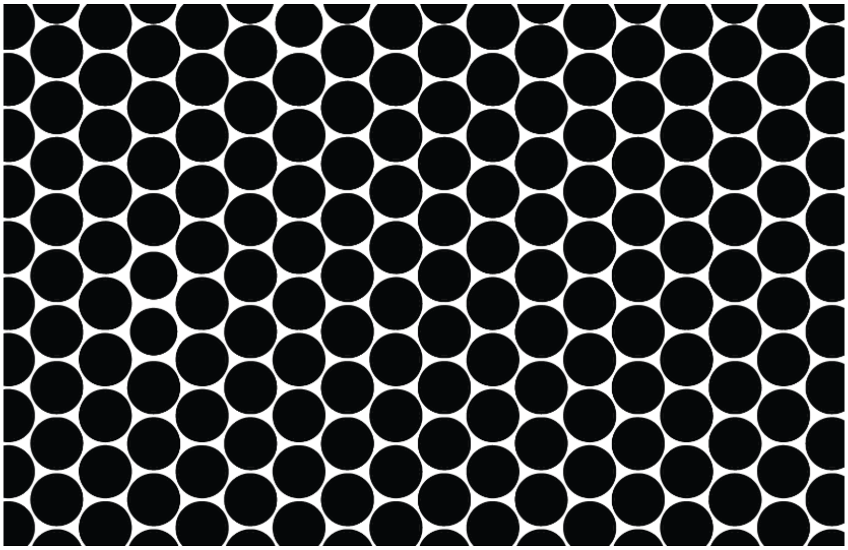


Figure 1. Illustration of homogenous pore network.

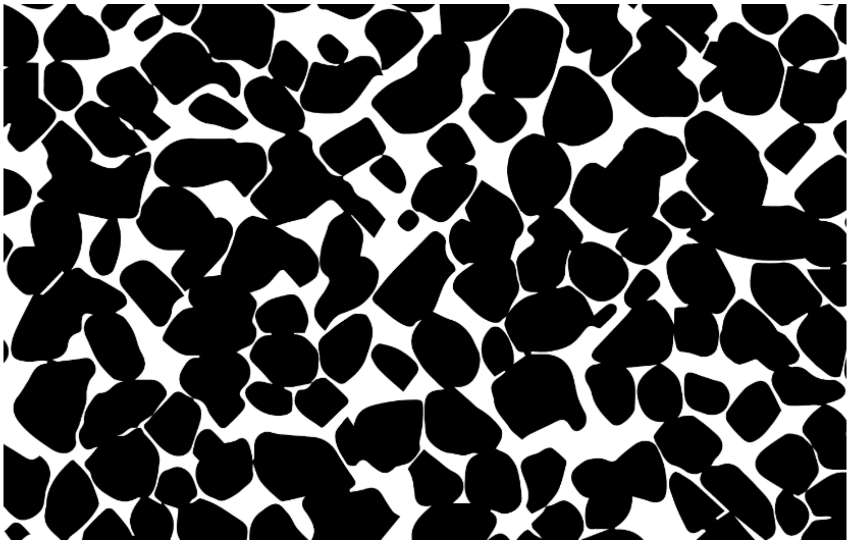


Figure 2. Illustration of heterogenous pore network based on a microscopic image.

ii. Software Implementation

The toolkit that was used to 3D print the micro-models was pre-developed at Texas A&M University at Qatar (Seers and Alyafei, 2018) (**Figure 3**). The toolkit was developed using the MATLAB language and executed via a graphical user interface. The program MATLAB was used for this application due to the existence of an extensive catalogue of native function libraries for image processing, visualization and analysis (e.g. Image Processing Toolbox, Computer Vision System Toolbox), as well as an active user base and associated third party open source code repository. The utilization of this tool is well established and tested.

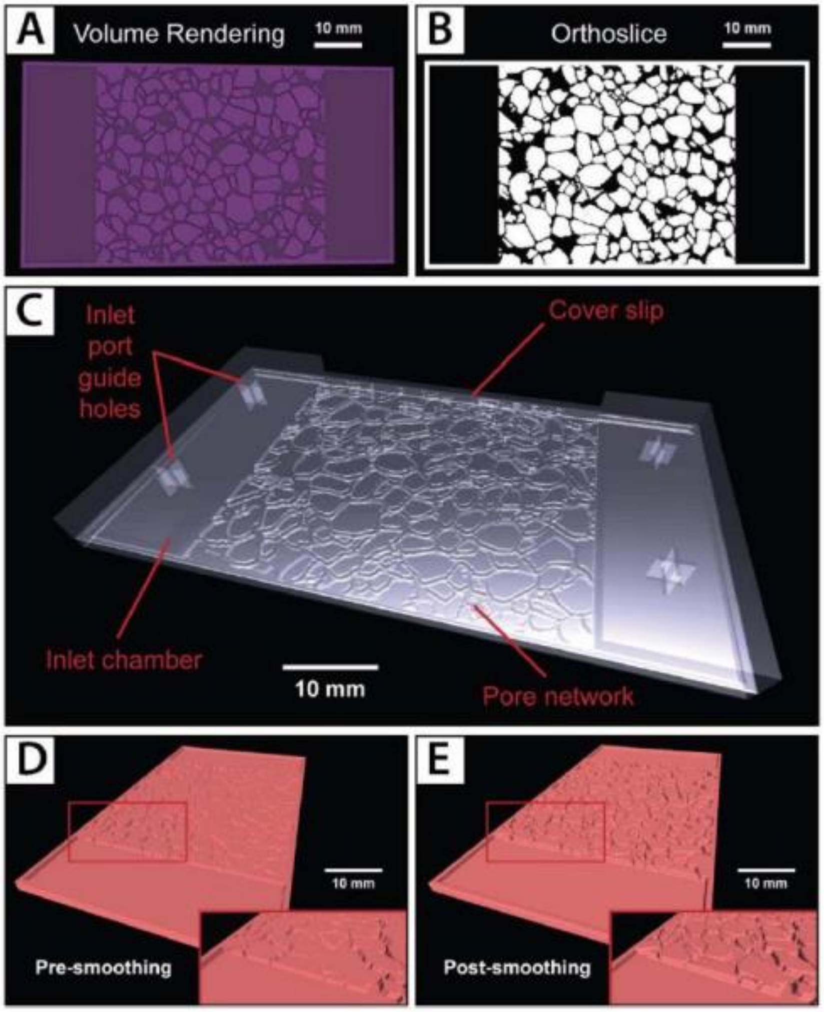


Figure 3. (A) Volume rendering of Berea Sandstone micromodel (coverslip removed). (B) Orthoslice of the upper most portion of A. (C) Transparent rendering of a mesh based representation of the Berea micromodel with constituent components indicated. (D) Tessellation of voxels results in 'blocky' mesh geometry. (E) Removal of voxel artifacts using Laplacian smoothing (Seers and Alyafei, 2018).

iii. Micro-model Construction

Using the open source toolkit, the synthetic porous media which contain standard micro-model components such as a pore network and inlet/outlet chambers were 3D printed. Printing was performed using the Dazz S130 SLA 3D printer. This method allows for standard/theoretical pore-network models (**Figure 4**) or real pore-network mimics from real porous rocks. The printing system is established and has been utilized previously to print pore-network models (**Figure 5**). The toolkit also produced guide holes for the location of inlet ports, which were installed post-fabrication by the user.

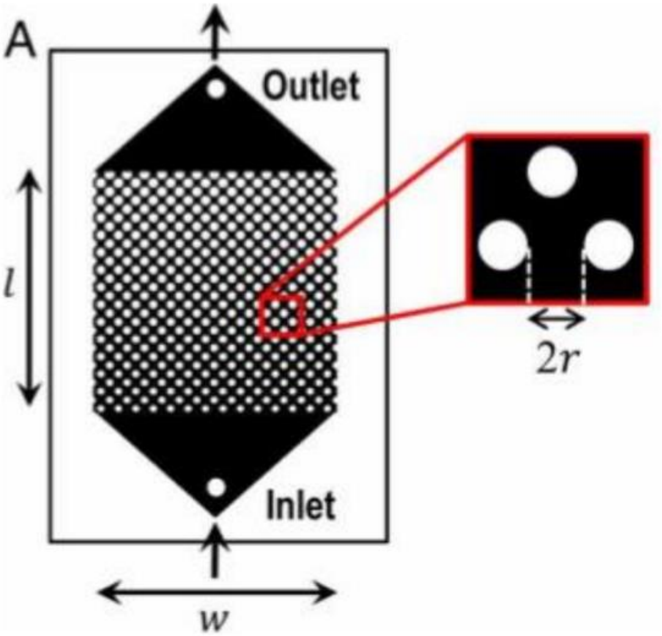


Figure 4. A 2D schematic of micro-model design with dimensions and an example of uniform homogenous porosity.

Figure 5. 3D printed micro-model using transparent resin (an example of heterogenous porous media).

iv. Mesh Post-processing

Post-fabrication, the micro-models are observed to have a blocky mesh surface geometry which introduces roughness artifacts into the output porous media. Laplacian mesh filters were implemented in order to remove surface roughness artifacts arising from the mesh generation process. To improve the appearance of the models on image and video, the top and bottom surfaces of each model were smoothed with a series of sanding paper followed by a coating of wax in order to reduce the translucent-mesh appearance (**Figure 6**). Furthermore, due to occurrence of bottlenecks in the processing of large (i.e. several to several tens of million face) triangular irregular network models by commercially available 3D printers, it is often necessary to reduce the face count of 3D meshes prior to being used as a template for additive manufacturing-based fabrication. Therefore, surface preserving mesh decimation functions were provided to reduce output models to data volumes that can be readily parsed by most 3D printers.

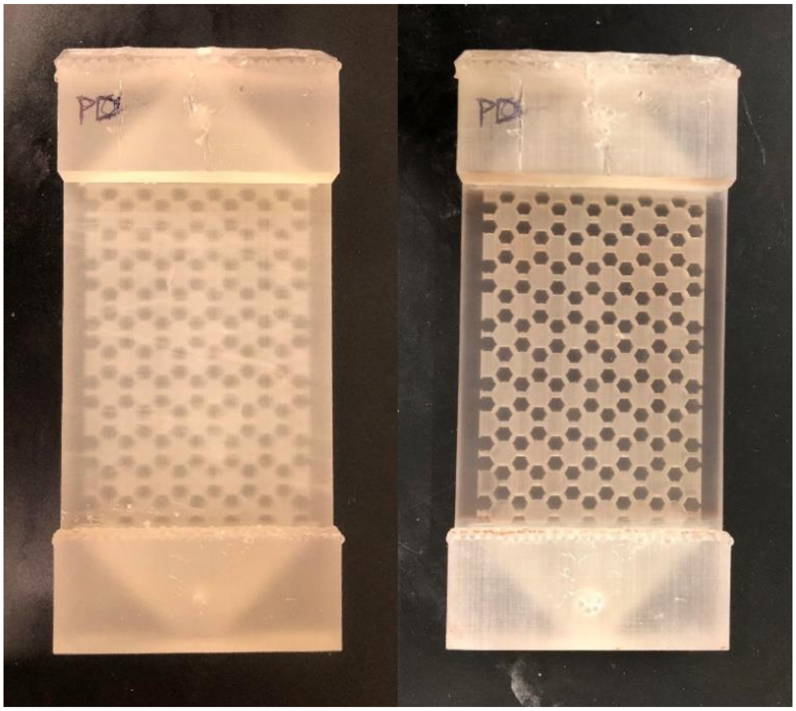


Figure 6. 3D printed micro-models before and after sanding and polishing.

v. Visualization Experiments

Once the micro-model was prepared, fluids were passed through it in an experimental setup (**Figure 7**). The fluids were doped with an optical contrast agent and injected using syringe pumps (**Figure 8**). The flow was observed using a bespoke fluid imaging apparatus commissioned in-house, consisting of a Z-Cam E1 RGB camera equipped with Olympus MFT mount macro lens, mounted upon a camera copy stand, with illumination provided by an adjustable LED light panel. Under such an experimental setup (**Figure 9**), viscous fingering as well as primary drainage and imbibition can be visualized and analyzed via time series image data, enabling both irreducible water saturation (S_{wir}) and residual oil saturation (S_{or}) to be quantified respectively. The research work also focuses on viscous fingering and capillary trapping effects.

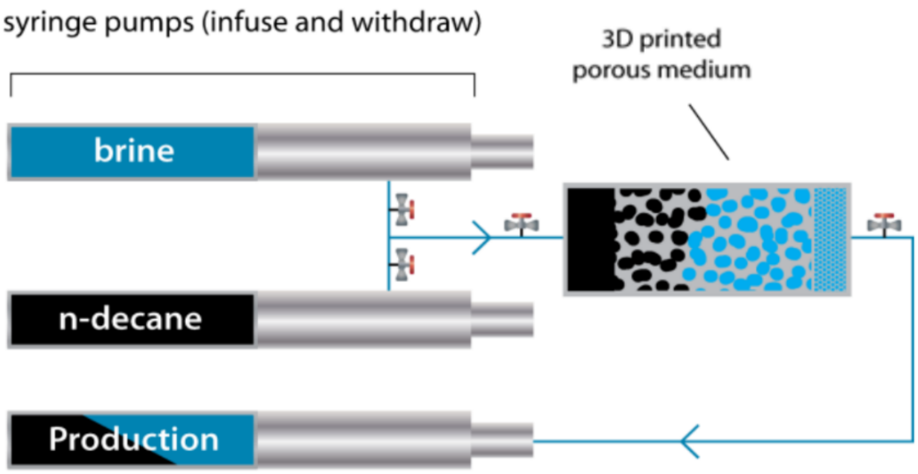


Figure 7. Experimental micro-model flow setup.

Figure 8. CONTEC SP500 Syringe Pump.

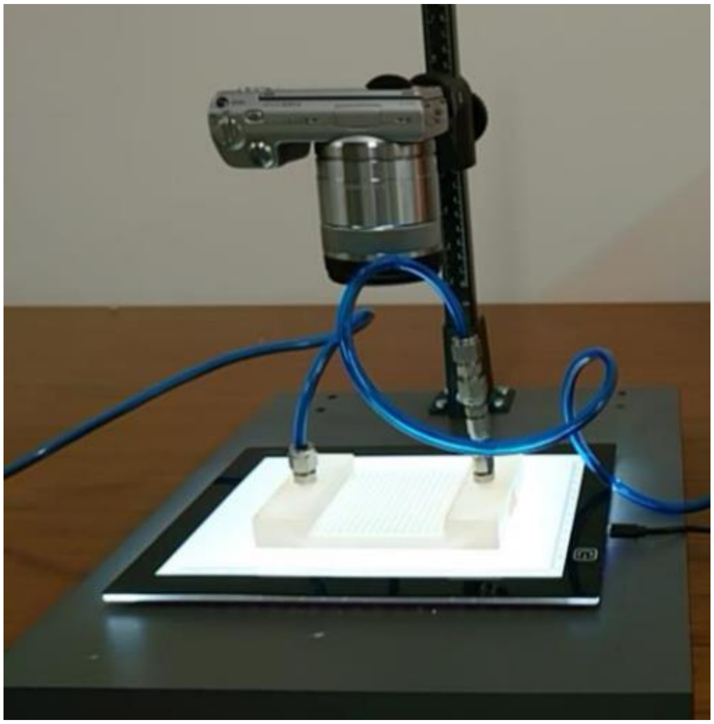


Figure 9. Flow experiments and visualization setup.

CHAPTER IV

RESULTS

After conducting all the necessary micro-model preparations, all models underwent flow experiments using the equipment and procedures mentioned above. Both drainage and imbibition experiments were conducted using water and oil. The obtained images and videos from both drainage and imbibition processes were used to quantify the irreducible water saturation (S_{wir}), residual oil saturation (S_{or}), and therefore the displacement efficiency (E_D), using the program ImageJ. Three phases were captured: (i) 100% saturated with water, (ii) drainage, and (iii) imbibition.

i. 100% Saturated with Water

The first image was taken of the model that is 100% saturated with water (**Figure 10**). The image was imported into the program ImageJ. The light-blue fluid is water and the yellow circles represent the matrix spaces.

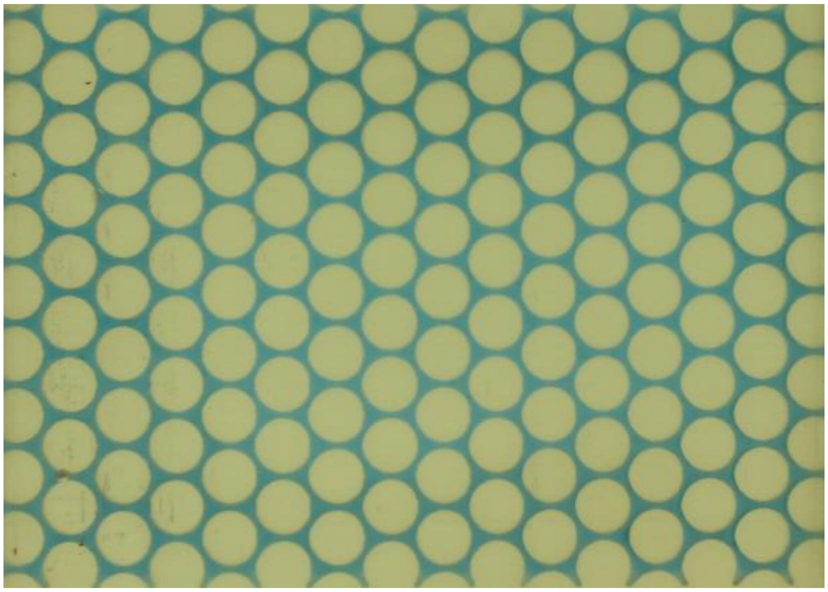
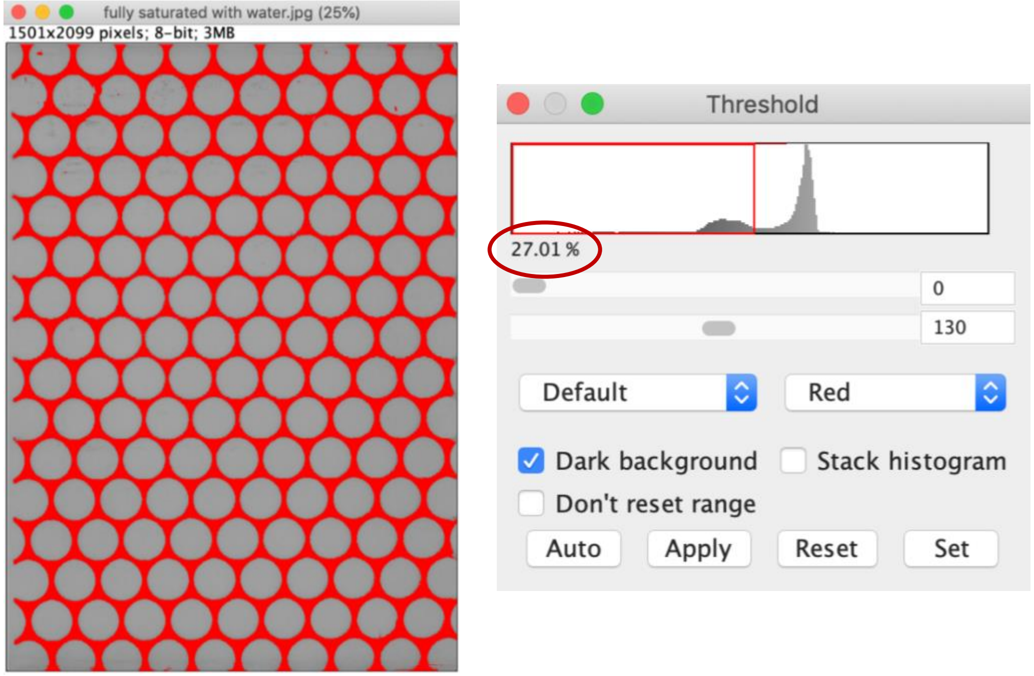


Figure 10. Homogenous pore-network micro-model 100% saturated with water.

The image was then changed into an 8-bit image, which turned the image into gray-scale. Then the threshold was adjusted such that the red mask only covers the pore spaces. The percentage that appears on the threshold window equals to the porosity value (**Figure 11**). In this case, the porosity equals to 27.01%.


fully saturated with water.jpg (25%)

1501x2099 pixels; 8-bit; 3MB

Threshold

27.01 %

0

130

Default

Red

☑ Dark background

☐ Stack histogram

☐ Don't reset range

Figure 11. Threshold over the pore spaces to quantify the porosity in ImageJ.

ii. Drainage

Drainage is the displacement of a wetting phase by a nonwetting phase, which in this case is injecting oil to displace the water. The image taken during this process (**Figure 12**) was imported into the program ImageJ. The dark-red fluid is oil.

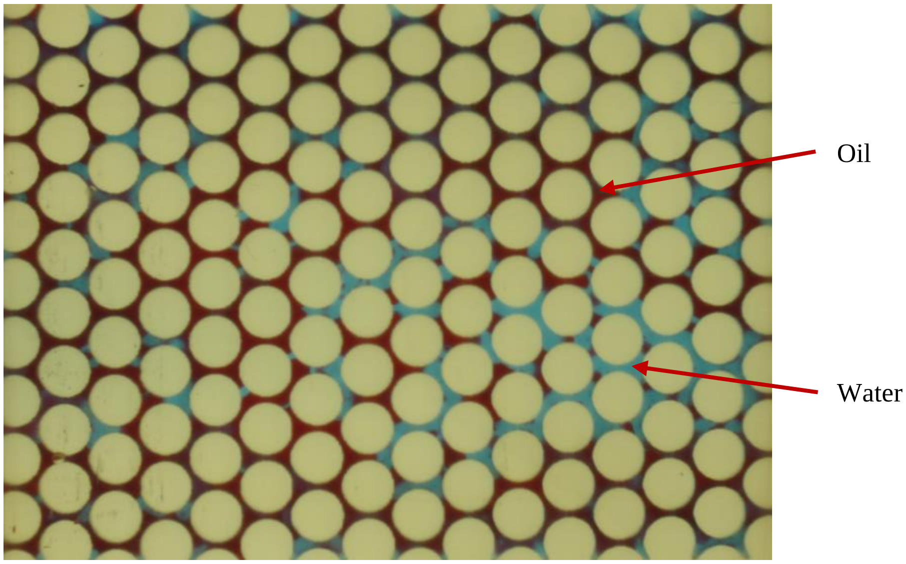
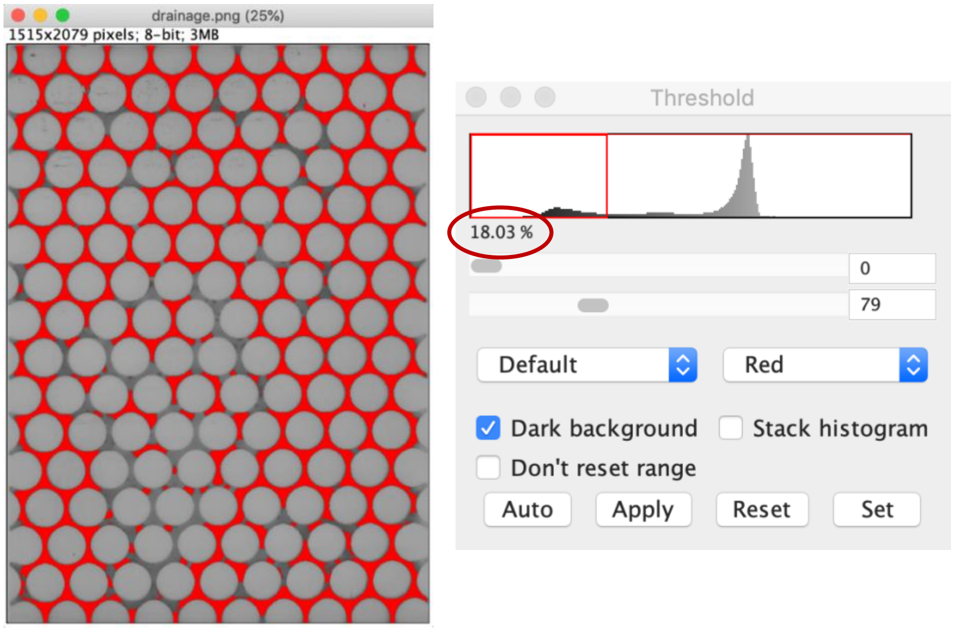


Figure 12. Homogenous pore-network micro-model during the drainage process.

Similar to the previous procedure, the image was transformed into an 8-bit image. Then the threshold was adjusted until the red mask only covers the pore spaces occupied by oil. The percentage that appears on the threshold window equals to the portion of the model occupied by oil (**Figure 13**). In this case, the model is 18.03% occupied by oil.



drainage.png (25%)

1515x2079 pixels; 8-bit; 3MB

Threshold

18.03 %

0

79

Default

Red

☑ Dark background

☐ Stack histogram

☐ Don't reset range

Figure 13. Threshold over the portion of pore spaces occupied by oil.

The oil saturation (S_o) can be calculated by dividing this percentage by the porosity obtained in section (i) as shown by **Equation 1**.

$$S_o = \frac{threshold\ \%}{\varphi} = \frac{18.03}{27.01} = 0.668 \quad \textbf{(1)}$$

Then using this value, the irreducible water saturation (S_{wir}) after drainage can be calculated using **Equation 2**.

$$S_{wir} = 1 - S_o = 1 - 0.668 = 0.332 \quad \textbf{(2)}$$

This means that for this specific model, or rock pore-network, the percentage of water that was not able to be displaced by the oil is 33.2%.

iii. Imbibition

Imbibition is the displacement of a nonwetting phase by a wetting phase, which in this case is injecting water to displace the oil. This process was done following the drainage experiment once the irreducible water saturation has been reached. The image taken during this process (**Figure 14**) was imported into the program ImageJ.

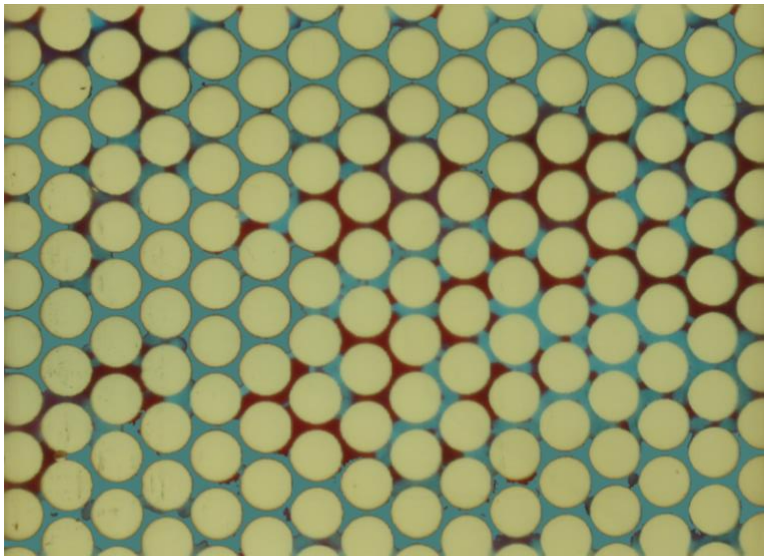
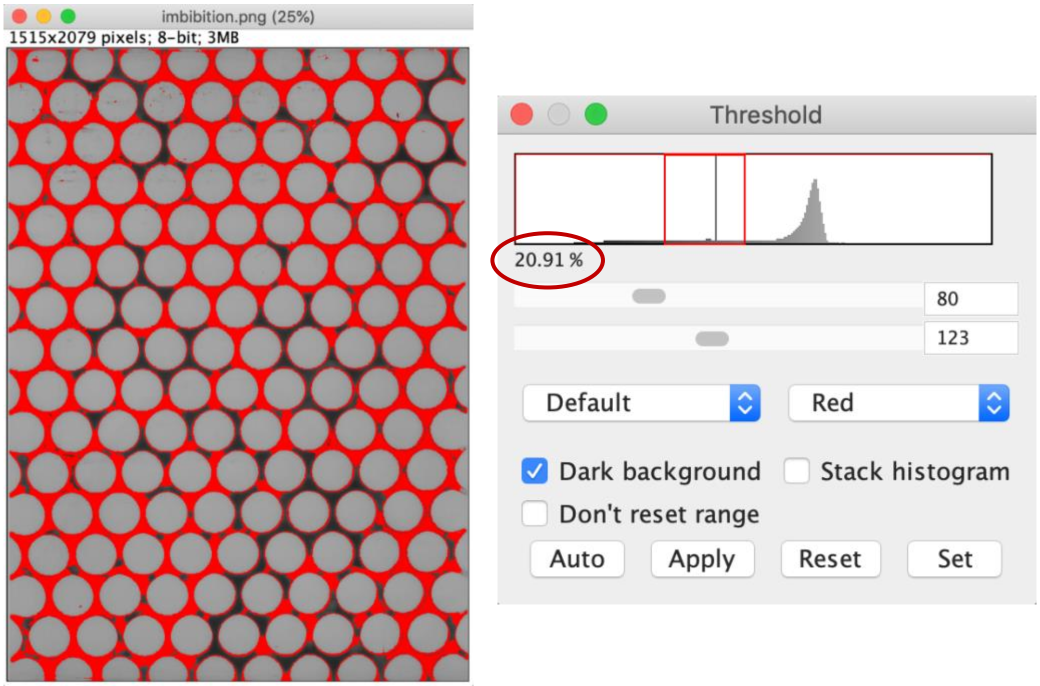


Figure 14. Homogenous pore-network micro-model during the imbibition process.

After importing and editing the image into an 8-bit type using the ImageJ program, the threshold was adjusted until the red mask only covers the pore spaces occupied by water. The percentage that appears on the threshold window equals to the portion of the model occupied by water (**Figure 15**). In this case, the model is 20.91% occupied by water.



20.91 %

80

123

Default

Red

☑ Dark background

☐ Stack histogram

☐ Don't reset range

Figure 15. Threshold over the portion of pore spaces occupied by water.

The water saturation (S_w) can be calculated using **Equation 1**, which was found to be 0.774 or 77.4%. Using this value, the residual oil saturation (S_{or}) after imbibition can be calculated using **Equation 3**.

$$S_{or} = 1 - S_w = 1 - 0.774 = 0.226 \qquad \mathbf{(3)}$$

This means that for this specific model, or rock pore-network, the percentage of water that was not able to be displaced by the water is 22.6%.

iv. Displacement Efficiency

The displacement efficiency (E_D) is the fraction of the oil displaced from each pore by the injected water. This value can be calculated using **Equation 4**:

$$E_D = \frac{1 - S_{wir} - S_{or}}{1 - S_{wir}} = \frac{1 - 0.332 - 0.226}{1 - 0.332} = 0.662 = 66.2\% \tag{4}$$

In industry terms, this value means that 66.2% of the oil has been recovered by the displacement process. Oil recovery ranges from field to field. However, on average, the ultimate oil recovery after immiscible fluid injection processes ranges between 30% to 35% of the original oil in place (OOIP). This difference in values can be due to numerous factors, including the wettability of the micro-model and the difference in capillary pressures within the pore systems, which is expected to be very low in the micro-model as it is significantly bigger in size compared to size of real rock pore-networks. It is also expected for homogenous pore-systems to have greater oil recoveries.

CHAPTER V

CONCLUSION

This research project implemented a new technique determining if extraction from a specific reservoir would be economically feasible or not. Fluid flow and saturation distributions at the pore scale were studied using mobile, inexpensive laboratory equipment. 3D-printed transparent micro-models, created from image processing of actual rocks, were used in this study in order for users to study transport phenomena and rock physics workflows at pore scale. The results from this project will be beneficial for both academic purposes and a new way for companies to determine a field's potential prior to production.

Other than calculating for the porosity of the micro-model, drainage and imbibition processes were implemented to quantify the irreducible water saturation (S_{wir}), residual oil saturation (S_{or}), and therefore the displacement efficiency (E_D), using the program ImageJ. In this report, only a homogenous sample was used to show the basic calculation procedures.

To further improve on this project, or for similar research surrounding this topic, it is recommended to perform the above procedures for heterogenous pore networks and compute for the porosity, irreducible water saturation, residual oil saturation, and displacement efficiency. It would also be advised to repeat experiments for higher accuracy.

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