CFD Simulation of the Oil Displacement in Micromodel for Enhanced Oil Recovery Application

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Abstract. Diminishing hydrocarbon reserves in oil reservoirs and the need to sustain continuous oil production have prompted researchers to further investigate Enhanced Oil Recovery (EOR) techniques. Researchers also test run these processes before EOR fluid injection into the reservoir to maximise oil production whilst minimising reservoir damage and fluid loss. This study aims to simulate oil displacement during the injection of two different types of EOR injection fluid, namely of water and polymer, using a commercial CFD software known as ANSYS Fluent. A heterogeneous 2D micromodel that has randomised pore network was selected as the basis of the flow system. By doing so, it is hoped to replicate a reservoir prototype using an innovative approach in a 2D geometry that appropriately simplifies complex reservoir properties represented. Initially, micromodel is fully saturated with crude oil. Then, water and polymer are injected separately on a case-to-case basis at flowrate of 0.8 mL/min. Visual inspection of the phase fraction contour results found that polymer flooded micromodel had smaller regions of oil volume fraction as compared to that of water flooded micromodel. Polymer flooded micromodel also had smaller and more branched fingering front as compared to water flooded micromodel. The analysis found that polymer flooding had better oil displacement efficiency as compared to traditional water flooding due to higher mobility ratio, reduced viscous fingering and lower residual oil saturation.

1. Introduction

Enhanced oil recovery (EOR) has been widely implemented as a tertiary oil recovery method to churn out more oil from dwindling hydrocarbon reserves located in hostile terrains such as the artic and ultra-deep seas. This method primarily targets heavy oil which remains trapped in the reservoir, by injecting a substance into the wellbore to lower oil viscosity and increase pressure to mobilize hydrocarbons to a production well. The technologies currently available under EOR are categorized into thermal methods, chemical methods, gas injection and others. In this study, the chemical method was the main subject of interest, and among nanofluid, alkali, foam, surfactant and polymer flooding, polymer flooding was selected.

Recent interest in microfluidic devices from the petroleum industry has propelled the development of different micromodel configurations to represent or replicate reservoir conditions and properties [1]. Unlike the conventional core samples extracted from the reservoir for flooding experiments, micromodels have been preferred since they have lower equipment cost, repeatable instrument use, and transparency for better flow visualization [2]. Micromodels usually contain channel widths as thin as 10-100 micrometres and study flow in smaller volumes as compared to other apparatus [2,3]. The micromodel designs can be categorized, namely into innovative [4-6], Voronoi Tessellations [7,8] and
reservoir prototype-based designs [9,10]. A collection of designs by Gharibshahi et al. (2015) [5] utilizes innovative designs with simple periodic geometries of circular grains. Most works report replicating a portion of the thin cross-section of core sample taken from SEM images [9,10]. Other works report using Voronoi tessellations in the design for pore-throat connectivity [7,8].

Computational fluid dynamics (CFD) is another useful approach taken to study oil displacement and interaction of fluids in the system. CFD has gained growing recognition and use among the researchers in the chemical [11,12] and petroleum engineering field [13,14]. It produces a quantitative prediction of fluid flow phenomena based on the laws of conservation of mass, momentum and energy that govern fluid flow. It is also a numerical approach used to solve complex three-dimensional and time-dependent flow problems due to the limited scope of analytical solutions available to fundamental equations of fluid mechanics. A comprehensive review by Jafari et al. (2019) [15] documented that EOR simulations at the reservoir, well and micromodel scales can be achieved using the commercial CFD softwares available including ANSYS CFX, COMSOL Multiphysics [16] and Fluent [17] respectively.

Both laboratory EOR studies using core samples and micromodel apparatus experiments have a limitation. Both methods do not have the ability to manipulate the core and micromodel properties since core sample has already been extracted from the reservoir and physical micromodel already fabricated based on a fixed design. The core flooding experiment typically suffers the demerit of alteration of the rock sample such as drilling to set-up to equipment. After one use, the core no longer can be used due to flooding fluid already contaminating the sample. The micromodel as an apparatus, on the other hand, is more flexible as it can allow various experimental runs and different conditions as well as multiple fluids to flow through it. Although fluid properties and initial conditions can be manipulated, the effect of varying pore geometry, grain size and throat sizes cannot be studied comprehensively to the process [1,2]. Besides that, both experimental techniques are not able to investigate various critical conditions, as they both incur the cost of EOR chemical usage or are dangerous to reproduce such conditions.

Furthermore, the flow pattern and oil displacement movement cannot be predicted and studied at each point of the system by varying the conditions. In other words, minimal and non-holistic information of each property in the current can be obtained from the experimental runs. A more practical solution to approach this problem is by running CFD simulations which require lower cost and provides the user with more flexibility to simulate the flow under various conditions. Various designs of micromodel in terms of their permeability, porosity, heterogeneity and dimensions can be generated to evaluate possible scenarios in EOR processes. This evaluation at the microscale level can later be upscaled to reservoir scale using the method of averaging [13,15].

Although reservoir prototype based and Voronoi tessellated micromodels bear actual resemblance to the actual core sample and have a well-randomized pattern of pores-throat, parameters due to micromodel configuration that affects fluid flow such as permeability, porosity and pore-throat ratio cannot be studied singularly due to complex and randomized patterns. Besides that, there is a paucity of literature investigating polymer flooding using CFD simulation at micromodel scale whilst feeding it with relevant polymer flooding experimental data from previous works and to test its validity with experimental results. Hence, this study aims to develop a suitable micromodel computational domain based on an innovative approach using ANSYS Fluent and to simulate the flow of oil displacement using an appropriate CFD model to represent the flow of oil to injection fluid accordingly. This study goes on to investigate the effect of two different injection fluids (water and polymer) based on the volume fraction phase contours generated. The effect of residual oil saturation, reflecting on the oil recovery for both flooding scenarios were then evaluated.

2. Methodology
The methodology of this study can be broken down into three distinct stages, namely the pre-processing, solver and post-processing stage.
2.1. Base Case Selection
Before moving into the pre-processing stage, the base model must first be selected to establish a good agreement between CFD simulation and the physical model and validate the model applicability in the current study. A review of existing literature found an appropriate micromodel design capable of reproducing oil recovery results similar to experimental results with the lowest deviation of 5.17% in terms of the oil recovery factor as reported by Gharibshahi et al. (2015) [5]. The micromodel is designed with the inlet (lower-left corner) and outlet (upper right corner) to represent one-quarter of the five-spot flooding pattern. The micromodel design is a 2D geometry consisting of 123 circles randomly distributed within a square model to ensure that porosity is generally maintained at 33% [5].

2.2. Pre-Processing

2.2.1. Geometry Creation. The micromodel geometry of the companion case was reproduced using SpaceClaim. The technique used to reproduce this design was by manually tracing the micromodel geometry based on an image from [5]. The image was scaled to obtain an approximately 60 mm by 60 mm, 2D quadrilateral shape before tracing. Furthermore, a surface was generated from the sketch while deleting the circular shape, so that hollow regions existed instead of the grains. The final geometry generated is as shown in Figure 1.

![Figure 1: Space Claim drawing of traced micromodel geometry](image)

2.2.2. Meshing. In this study, two types of mesh were generated based on the mesh type. The first mesh uses quadrilateral dominant meshing method while the second mesh uses triangular meshing method, both with adaptive sizing of mesh resolution = 4 as shown in Figure 2. The mesh generated obviously differs from each other upon visual inspection and their differences will be discussed in later section.
2.3. Solver

2.3.1. VOF: Governing Equations. Since a multiphase flow exists in this study, the characterisation of the flow regime is the first step in choosing a multiphase method. The Volume of Fluid (VOF) model was selected to run both water and polymer flooding cases as it was designed specifically for a multiphase flow with two or more immiscible fluids. The VOF model is also a convenient surface tracking technique that can be applied to a fixed Eulerian mesh.

In the VOF Model, a single set of momentum equations is solved while tracking the volume fraction of each of fluids throughout the domain. It models two or more immiscible fluids so that fluids are not interpenetrating. Each control volume must be filled with either a single fluid phase or combination of phases.

If \( q^{th} \) fluid’s volume fraction in the cell is denoted as \( \alpha_k \), three conditions are possible according to phase equations.

\[
\begin{align*}
\alpha_k &= 0; \text{ The cell is empty (of } q^{th} \text{ fluid)} \\
\alpha_k &= 1; \text{ The cell is full (of } q^{th} \text{ fluid)} \\
0 < \alpha_k < 1; \text{ The cell contains the interface between the } q^{th} \text{ fluid and one or more other fluids.}
\end{align*}
\]

The tracking of the interface(s) between the faces is done by solving the continuity equation for the volume fraction of the phases. For the \( q^{th} \) phase, the continuity equation is given, as shown below.

\[
\frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) \right] = S_{\alpha_q} + \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp})
\]

(1)

where \( \rho_q \), \( \vec{v}_q \), and \( \dot{m}_{qp} \) represents the density of phase \( q \), and mass transfer from phase \( q \) to phase \( p \), respectively. By default, the source term on the right-hand side of the equation, \( S_{\alpha_q} \) is zero. Where appropriate, a constant or user-defined mass source for each source can be specified.

The volume fraction equation is not solved for the primary phase. The volume fraction of primary phase was computed based on the following constraint.
\[ \sum_{k=1}^{n} \alpha_k = 1 \]  \hspace{1cm} (2)

In a general n-phase system, the volume fraction averaged density is presented in the following form.

\[ \rho = \sum \alpha q \rho q \]  \hspace{1cm} (3)

Other properties such as viscosity will be computed in a similar manner. A single momentum equation is solved throughout the domain with resulting velocity field shared among the phases. The momentum equation is dependent on volume fractions of all phases through properties \( \rho \) and \( \mu \).

\[ \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla \cdot [\mu (\nabla \vec{v} + \nabla \vec{v}^T)] + \rho g \vec{g} + \vec{F} \]  \hspace{1cm} (4)

2.3.2. Data Input. The data input required to the solver includes the material properties of the fluids, the operating conditions and the initial and boundary conditions. The properties of both oil and polymer adopted in this project are based on experimental work [18] and simulation paper [10] respectively. The phase interaction can be captured by modelling the surface tension between the primary and secondary phases. The properties of the three fluids mentioned above were catalogued accordingly as shown in Table 1.

| Table 1 Properties of fluids |
|-----------------------------|
| Fluid Properties | Displaced Fluid | Displacing Fluid |
| Name | Crude Oil | Polymer | Water |
| Density | 900 kg/m$^3$ | 1302 kg/m$^3$ | 998.2 kg/m$^3$ |
| Viscosity | 450 cP | 200 cP | 1.003 cP |
| Surface tension (oil-displacing fluid) | - | 0.012 N/m | 0.0574 N/m |

2.3.3. Initial and Boundary Conditions. The boundary conditions and operating conditions for this study were adopted from both [5] and [10] respectively. The following assumptions were made to simplify the model applied.

- Two-phase flow condition
- Oil as primary phase, water and polymer as a secondary phase
- Initial water saturation is zero \( (S_{wi} = 0) \) and water injected into the micromodel is distilled water
- Transient state condition
- The injection flow rate is kept constant at 0.8 mL/min for both fluids.
- Time interval of \( \Delta t = 0.1 \) s selected for all simulations.
- The simulation was run for 100-time steps (water flooding) and 200-time steps (polymer flooding) with a maximum iteration of 1000.
2.4. Post-processing

In the post-processing stage, the volume fraction contour plots for both polymer and water flooding were extracted as one of the qualitative results. This was to compare flow with physical model and for better flow visualisation and observation of oil displacement.

3. Results and Discussion

3.1. Mesh Assessment Quality

Table 2 reports the results of quality assessment of both mesh types generated.

| Mesh Method                  | Quad-dominant | Triangular               |
|------------------------------|---------------|--------------------------|
| Adaptive Sizing Resolution   | 4             | 4                        |
| Number of nodes              | 4947          | 5112                     |
| Number of elements           | 3542          | 7371                     |
| Mesh Quality                 |               |                          |
| Element Quality (>0.90)      | 163 elements (4.6%) | 5677 elements (77%)       |
| Orthogonal Quality (>0.90)   | 2960 elements (84%) | 5801 elements (79%)       |
| Skewness (<0.25)             | 1878 elements (53%) | 6696 elements (90%)       |

Based on Table 2, it was found that the triangular meshing method generated a higher number of elements and nodes as compared to the quadrilateral dominant meshing method. A more significant number of elements and nodes generally suggest that triangular mesh is slightly more refined than quadrilateral dominant type. It is an early indication that computational time required to perform CFD calculations on triangular mesh would be longer than quadrilateral mesh type. Based on the three mesh quality criterion evaluated, it was found that triangular mesh had better quality as compared to quadrilateral dominant mesh. A more significant percentage of mesh elements of the triangular scheme had higher element quality and orthogonal quality accompanied by lower skewness as compared to that of quadrilateral dominant. Hence, it can be inferred that triangular mesh is more likely to give better convergence and more accurate solution. Therefore, the triangular meshing method has a greater number of nodes and elements, making it more refined than that of quadrilateral dominant meshing, which is more likely to incur longer computational time during solver stage. However, the triangular mesh is more likely to produce better mesh quality and result in a more accurate, converging numerical solution.

Visual results of volume fraction plots under both water and polymer flooding conditions further confirms the above statement. In each case of water and polymer flooding, the quadrilateral dominant mesh produces a larger displacement font as can be seen in Figure 3. The computational time required to displace oil from inlet to outlet using a quadrilateral mesh discretization scheme is shorter than that of triangular mesh. In other words, the calculation solved at each element of the domain for the quadrilateral-dominant mesh is faster than triangular mesh. The quadrilateral dominant mesh is also characterised by smaller areas of red contour or regions of oil flow as compared to that of triangular mesh. This observation is verified by the fact that the displacing front is more developed in a quadrilateral dominant mesh than triangular meshing referred to above due to mesh fineness.
Figure 3: Water flooding in (a) Quadrilateral dominant mesh and (b) Triangular mesh within 10 s (top row: from left to right) (red indicates oil flow region, blue indicates water flow region); Polymer flooding in (c) Quadrilateral mesh and (d) Triangular mesh within 20 s (bottom row: from left to right) (red indicates oil flow region, blue indicates polymer flow region)

3.2. Water Flooding vs Polymer Flooding
The analysis below uses triangular meshing scheme as a basis of comparison in both water and polymer flooding cases due to higher quality of results as discussed earlier. Based on Figure 4, water flooding results show larger regions of oil contours still trapped in micromodel as compared to that of polymer flooding. Besides that, the flooding front of water is composed of fewer branched fingers of larger magnitude while the polymer front has more branched fingers of smaller magnitude. Moreover, the time taken for water to reach the outlet is shorter (10 s) as compared to that which is required by polymer (20 s).

Figure 4: Oil volume fraction plot of (a) water flooding and (b) polymer flooding using triangular mesh as a basis of comparison.
The difference in the oil volume fraction profiles of both water and polymer flooding can be explained based on the concept of sweep efficiency, which is also known as the macroscopic oil efficiency. The ultimate oil recovery is dependent on the overall displacement oil efficiency in a crude-oil-brine-rock (COBR) system, which in turn is measured by the product of the microscopic (pore-scale) and macroscopic (sweep) oil efficiency. However, the analysis in this system is limited to sweep efficiency. Sweep efficiency measures the effectiveness of the displacing fluid to sweep both lateral and areal (volumetric) extents of the reservoir as well as to move displaced oil towards the displacement wells.

Sweep efficiency is further characterized by fractional flow, reduction of displacing fluid-oil mobility ratio and by the diversion of injected fluid toward swept zones [19]. Analysis of water flooding results is consistent with the occurrence of fingering with minimal regions of oil contacted with water. Viscous fingering occurs due to water injected being less viscous than oil which increases water-oil mobility ratio and causes the displacement of oil to be quite unstable [6]. As a result, an uneven sweep that forms water fingers at the flood front are obtained. The uneven water sweep bypasses many regions of oil due to the high mobility of water which results in a higher residual oil saturation, low sweep efficiency and lowered oil recovery. The unstable front also leads to an early breakthrough of fluid.

On the other hand, the polymer flooding flow profile is characteristic of a better oil displacement efficiency due to the lower residual oil saturation. More oil regions were contacted with polymer and sweep front is more stable as it took a longer time to reach the outlet. The sweep front is also more evenly distributed with more extensive sweep coverage of the oil regions evenly, which will improve oil recovery. It is because the polymer solution has a higher viscosity as compared to water, which reduces the polymer-oil mobility ratio.

Hence, the VOF model applied as the CFD model successfully simulated the flow in an immiscible displacing fluid-displaced fluid system of water-oil and polymer-oil. The analysis of results, as discussed above, supports previous experimental and simulation studies [10,18] conducted to investigate the displacement efficiency of water and polymer solutions injected into the oil. Polymer flooding improves the traditional water flooding by increasing displacement fluid and mobility ratio, and reducing viscous fingering. This subsequently increases sweep efficiency and oil recovery by decreasing residual oil saturation.

4. Conclusion
In conclusion, investigation of both water flooding and polymer flooding in a 2D micromodel was performed using a constant injection flow rate of 0.8 mL/min in ANSYS Fluent. The geometry and configuration of the micromodel, which is designed to resemble a quarter of the five-spot flooding technique from injection port to the production port. In water flooding, larger and more distinct finger patterns were formed as compared to polymer flooding where smaller and highly branched fingers are formed. The residual oil saturation in micromodel at the end of simulation time in water flooding is higher than that of polymer flooding. A larger area of displacement font which covers most of the micromodel is observed in polymer flooding as compared to water flooding is observed at the end of the simulation. The time taken for injection fluid to travel from inlet to outlet in polymer flooding is longer than that of water flooding. In terms of oil recovery, since the residual oil saturation in water flooding is higher, a lower oil recovery is indicated and vice versa for polymer flooding. Although polymer flooding takes a longer time for injection fluid to reach the outlet (20 s) as compared to water (10 s), it is due to a wider spread of injected polymer which typically indicates a broader area coverage and hence improved oil displacement efficiency. Hence, the results show that polymer flooding improves traditional water flooding by increasing sweep efficiency and reducing viscous fingering, which increases oil recovery and lowers residual oil saturation.

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