Experiment and Numerical Studies of First Contact Miscible Injection in a Quarter Five Spot Pattern

By

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A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC in Petroleum Engineering.

September 2014
DECLARATION OF OWN WORK

I declare that this thesis “Experimental and Numerical Studies of First Contact Miscible Injection in a Quarter Five Spot Pattern” is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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Abstract

This study investigates the impact of mobility ratio and simple heterogeneities on the performance of first contact miscible gas flooding using both experimental and numerical models. It also examines the validity of using a commercial numerical simulator to model miscible injection for use in further studies. The study focuses on a quarter five spot pattern, using two 2D horizontal analogues of flow in porous media. Numerical simulations are conducted using the Eclipse-100 simulator, whilst physical experiments are carried out using a Hele-Shaw cell (40×40cm) designed and constructed for this study. The impact of a square low permeability inclusion (20×20cm) on flow was investigated by varying its permeability, location and orientation. The setup of the numerical model for a quarter five spot pattern proved to be challenging due to the extensive grid orientation effect and difficulty in triggering the formation of fine viscous fingers. This was partially resolved by using a nine-point pressure difference scheme and randomly generated permeability values across the whole grid, with a ±30% range around the calculated permeability.

The general conclusion for the study is that the Eclipse-100 numerical simulator is able to model the miscible injection in a quarter five spot pattern in a 2D system without gravity within an uncertainty range at lower mobility ratios (M=2 to M=10). Although at higher mobility ratios (M=20 to M=100) some new solutions are needed to reduce the grid orientation effect, which leads to overestimations of the areal sweep results. Nevertheless at M=20, the introduction of heterogeneities reduces the discrepancy between experimental and numerical results, and brings it back within uncertainty limits in some of the cases. This is mostly achieved because those certain heterogeneities compensate for the grid orientation effect by directing the flow around the heterogeneity box. This suggests that if an area of heterogeneity is small or it is close to a producer, it will not counteract for the grid orientation effect, because flow will not be spread enough. For the breakthrough times a good agreement between numerical and experimental results was observed at all mobility ratios. This shows that simulations could be used as a valid tool for some field scale studies where breakthrough time is of more concern rather than sweep pattern. One of the other important goals of this project that was achieved is to design and construct an experimental setup that could be used for an academic demonstration purposes.
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Contents

Title page .............................................................................................................................................. I
Declaration of own work .......................................................................................................................... II
Acknowledgements .................................................................................................................................. III
List of figures .......................................................................................................................................... IV
List of tables ............................................................................................................................................. V
Abstract ................................................................................................................................................... 1
Introduction ............................................................................................................................................. 1
Analogy between Hele-Shaw cell and flow in porous media, and prior studies ...................................... 2
Design of Hele-Shaw cell and experimental setup .................................................................................. 2
  Design and key parameters .................................................................................................................. 2
  Analogue Fluid ..................................................................................................................................... 3
  Experimental Setup ............................................................................................................................. 4
Modelling numerical simulations for a Hele-Shaw cell ............................................................................ 5
  Model setup ......................................................................................................................................... 5
  Population of the model with random permeability ............................................................................ 5
  Grid refinement and grid orientation study .......................................................................................... 6
Analysis and discussion of numerical and experimental results .............................................................. 8
  Analysis approach and uncertainties involved ..................................................................................... 8
  Mobility ratio variation study ............................................................................................................. 8
  Heterogeneity: Impact of the thickness .............................................................................................. 11
  Heterogeneity: Impact of the location ............................................................................................... 12
  Heterogeneity: Impact of the orientation ........................................................................................... 13
Summary and Conclusions ................................................................................................................... 15
Suggestions for further improvement and research ............................................................................... 15
Nomenclature ......................................................................................................................................... 16
Abbreviations ......................................................................................................................................... 16
References ................................................................................................................................................ 16
Appendix A: Critical literature review and Milestones .......................................................................... vi
Appendix B: Photograph of two Hele-Shaw cells designed for an experimental runs ............................ vii
Appendix C: Experimental procedure .................................................................................................. viii
Appendix D: Calculated relative permeability curves for modelling miscible injection at different mobility ratios ......................................................................................................................... viii
Appendix E: Comparison of numerical simulation runs with nine-point and five-point pressure difference schemes at M=20 using a diagonal grid ........................................................................ x
Appendix F: Eclipse-100 data file used for simulation of 0.12mm heterogeneous box in the centre of the cell at M=20 ............................................................ xi
Appendix G: Comparison of numerical simulation results for diagonal and parallel grid with nine point pressure scheme and parallel grid with five point pressure scheme to experimental results at M=20 ................................................. xiv
Appendix H: Areal sweep and breakthrough time results together with uncertainties for figures presented in the main body ... xv
List of Figures

Fig. 1 - Schematic of the Hele-Shaw cell design constructed using two 50×50×1.2cm polycarbonate plates ................................................. 3
Fig. 2 - Photograph of the experimental setup with description of all parts ............................................................................................... 4
Fig. 3 - Variation in the results for different parameters at 1PVI with the introduction of different ranges of random permeability values populated over the whole grid using 400×400 grid size and M=20 (a) Range of the results for total oil production. (b) Range of the results for a breakthrough time ........................................................................ 6
Fig. 4 - Oil saturation maps for the different ranges of randomly generated permeability values generated by numerical simulations using 400×400 grid size and M=20 at 0.25PVI .......................................................... 6
Fig. 5 - Variation in the results for different parameters at 1PVI with the change in grid size and orientation using 30% variation in random permeability, 400×400 grid size and M=20 (a) Range of the results for the total oil production. (b) Range of the results for the breakthrough time. .................................................................................................................. 7
Fig. 6 - Oil saturation maps for the different grid sizes and orientations using 30% variation in random permeability, 400×400 grid size and M=20 at 0.25PVI .......................................................... 7
Fig. 7 - Change of the parameters with increasing numbers of cells in numerical model simulated using 30% variation in random permeability, 400×400 grid size and M=20. (a) Results for the total oil recovery. (b) Results for the breakthrough time. .................................................................................................................. 7
Fig. 8 - Oil recovery results for numerical simulation at different injection mobility ratios of M=2, 5, 10, 20, 50 and 100, compared to the processed effluent measurement from experimental runs in a Hele-Shaw cell for M=2, 5, 10, and 20. .... 8
Fig. 9 - Comparison of results between the numerical simulation and experimental runs carried out in a homogeneous model by mobility ratios. (a) Areal sweep. (b) Breakthrough time. Uncertainties for simulations are based on the initial study into the impact of random permeability application over the whole grid. Uncertainties for areal sweep in experiments are based on the study into the accuracy of colorimetry method and for breakthrough time based on the visual observations. All uncertainties are shown with error bars. .................................................................................................................. 9
Fig. 10 - Comparison of the oil saturation maps between experimental runs and numerical simulations in a homogeneous model. (a) M=2 at 0.25PVI (b) M=5 at 0.25PVI (c) M=10 at 0.25PVI (d) M=20 at 0.25 PVI (e) M=50 at 0.15PVI (f) M=100 at 0.15PVI (g) M=50 at 0.50PVI (h) M=100 at 0.50PVI .......................... 10
Fig. 11 - Comparison of the results for numerical simulation and experimental runs with different thicknesses of 20×20cm heterogeneity in the centre of the model. (a) Areal sweep results. (b) Breakthrough time results. Uncertainties for simulations are based on the initial study into the impact of random permeability application over the whole grid. Uncertainties for areal sweep in experiments are based on the study into the accuracy of colorimetry method and for breakthrough time based on the visual observations. All uncertainties are shown with error bars ........................................ 11
Fig. 12 - Comparison of the oil saturation maps between experimental runs and numerical simulations with a different thicknesses of 20×20cm heterogeneity in the centre of the model at 0.50PVI. (a) Homogeneous model. (b) 0.05mm heterogeneity. (c) 0.12mm heterogeneity. (d) 0.20mm heterogeneity .......................................................... 12
Fig. 13 - Comparison of the results for numerical simulation and experimental runs with different locations of 20×20cm heterogeneity of 0.12mm thickness. (a) Areal sweep results. (b) Breakthrough time results. Uncertainties for simulations are based on the initial study into the impact of random permeability application over the whole grid. Uncertainties for areal sweep in experiments are based on the study into the accuracy of colorimetry method and for breakthrough time based on the visual observations. All uncertainties are shown with error bars ........................................ 13
Fig. 14 - Comparison of the oil saturation maps between experimental runs and numerical simulations with a different location of 20×20cm heterogeneity of 0.12mm thickness at 0.50PVI. (a) Heterogeneity near the injector. (b) Heterogeneity in the centre. (c) Heterogeneity near producer. (d) Heterogeneity on the side of the main diagonal ........................................ 13
Fig. 15 - Comparison of the results for numerical simulation and experimental runs with different orientation of 20×20cm heterogeneity in the centre of the model. (a) Areal Sweep results. (b) Breakthrough time results. Uncertainties for simulations are based on the initial study into the impact of random permeability application over the whole grid. Uncertainties for areal sweep in experiments are based on the study into the accuracy of colorimetry method and for breakthrough time based on the visual observations. All uncertainties are shown with error bars. ........................................ 14
Fig. 16 - Comparison of the oil saturation maps between experimental runs and numerical simulations with a different orientation of 20×20cm heterogeneity in the centre of the model at 0.50PVI. (a) 0.12mm heterogeneity (b) 0.12mm rotated heterogeneity (c) 0.20mm heterogeneity (d) 0.20mm rotated heterogeneity ........................................ 14
List of Tables

Table 1 - Thickness of heterogeneities and the equivalent permeability in the zone of heterogeneity ........................................ 3
Table 2 - Physical properties of pure glycerol, water and their mixtures for different mobility ratios at 20°C .............................. 4
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Introduction
Miscible displacement is a widely used practice in the Oil and Gas industry as a method of secondary or tertiary oil recovery. The application of this method started in 1950’s (Stalkup 1983) and has proven to be advantageous compared to conventional waterflooding. It can reduce the viscosity of oil by 20-90% (Bray 1971), lower residual oil saturation and add significant incremental production in the range of 5-10% of oil initially in place (OIIP) (Christensen 2001). Miscible displacement can be split into two main categories: vertical and horizontal. Vertical miscible displacement is when solvent drives oil down as a “blanket” due to the density difference, as in miscible Gas-Oil Gravity Drainage (GOGD). Horizontal miscible displacement is similar to the conventional waterflooding, where the oil is simply pushed from injector towards producer. The difference is that it tends to switch from viscous dominated to gravity dominated flow, due to a substantial density difference between solvent and reservoir fluid, unless a high injection flowrate used and the distance between the well is relatively short (Muggeridge et al. 2002). For this reason and also because gas is more expensive to use it on its own, the horizontal miscible displacement is often used as a part of Water Alternating Gas (WAG) process, when water and gas are injected interchangeably in batches to ensure a better sweep efficiency.

In general vertical miscible displacement is more successful compared to the horizontal due to the stability of gravity displacement (Asgarpour 1994). However, some specific cases require the application of horizontal miscible displacement over vertical, for instance multi-layered reservoirs. In these cases the areal sweep plays a more significant role, thus it is important to understand it. The main factors affecting the areal sweep performance of miscible injection are well spacing, mobility ratio, pattern geometry and areal heterogeneities. At certain mobility ratios viscous fingering tends to lead to an earlier breakthrough than expected, hence it is important to test whether commonly used numerical simulators are able to replicate these processes. At the same time heterogeneities may cause some of the oil being bypassed and so the remainder needs to be quantified for its importance in secondary and tertiary recovery.

It is important to remember that numerical simulation is an analogue. It is a simplified representation of the processes happening in porous media and the solution of the equations is also an approximation. Commercial simulators solve the macroscopic Darcy equations, not the pore scale equations. Even though this method is well established there are still some aspects of the physics and chemistry of hydrocarbon reservoirs that are not well understood. Numerical simulations also struggle to correctly model some of the injection patterns at unfavourable mobility ratios, in particular a quarter five spot pattern (Fayers 1987). The problem arises from a grid orientation effect in a standard Cartesian grid. Christie (1989) suggested that one of the ways to reduce this effect could be the use of the nine-point pressure difference scheme instead of the standard
five-point. Yanosik and McCracken (1979) observed that the maximum difference in recovery is 1.5% between diagonal and parallel arrangement of grids using a nine-point pressure difference scheme in a quarter five spot pattern, however the study was carried out on a fully homogeneous 2D horizontal grid and did not model viscous fingers properly. Thus the best method of modelling miscible injection in a quarter five spot pattern has not been found yet.

The main goal of this study is to find out whether using a simple numerical model we can predict the miscible injection process in a quarter five spot pattern and in particular whether it can predict the viscous fingering correctly. If the numerical simulations are validated by experiments, they could be used to calibrate the parameters in empirical viscous fingering models for field application (Koval 1963; Todd and Longstaff 1972; Fayers 1988). With a further study some of the correlations could possibly be developed that could be used to adjust mixing parameter (ω) for Todd and Longstaff’s model or heterogeneity parameter (H) for Koval’s model. Fayers et al. (1992) also determined that for nonunit viscosity ratios in heterogeneous cases the heterogeneity parameter (H) could be implemented within the mixing parameter (ω) or mobility ratio (M) equations for Todd and Longstaff’s model.

The Hele-Shaw cell is an experimental method for validating numerical simulations. In this case we used the commercial simulator Eclipse-100. The following results are examined and compared: areal sweep, breakthrough time and total oil recovery. The study also provides a visual demonstration of the interaction between an unstable flow and different types of heterogeneities. Additionally it quantifies the uncertainties caused by the grid size and grid orientation. Finally it provides an experimental setup that could be used for demonstration purposes of unstable miscible displacements.

**Analogy between Hele-Shaw cell and flow in porous media, and prior studies**

Hele-Shaw cells are used as analogues of flow in porous media. They are constructed using two plates, with a very small gap between them - h/r << 1, where h is the gap thickness and r is the radial dimension. There are several advantages of using a Hele-Shaw cell instead of the standard bead pack model. One of the advantages is that there is no leading edge effect since there are no glass beads used in it. Another is having a better visual picture of the unstable flow and the formation of viscous fingers. The analogy between flow in porous media and Hele-Shaw cell does not seem obvious, however the equations describing single phase flow in a Hele-Shaw cell are exactly the same as the porous medium equations, the flow in both of them is governed by Darcy’s equations. The thickness of the cell has a direct relationship to the permeability of the system as illustrated in Eq. 1. (Greenkorn et al. 1964), where k is permeability and h is the height of the gap between the plates. The equations for first contact miscible displacement are also the same.

$$k = \frac{h^2}{12}$$

Having a simple relationship makes it possible to introduce heterogeneity to the system in a very controlled manner compared to the bead pack, and allows quantitative assessment of any numerical prediction. The magnitude of dispersion of one fluid into another is slightly different in Hele-Shaw cell than in porous medium and has a different velocity dependence. However this will be a secondary effect and could be modelled if necessary. The main effect in this experiment would be caused by changes in mobility ratio of the fluids and the presence of heterogeneities.

One of the earlier studies that examined the impact of unfavourable mobility ratio on the sweep efficiency in quarter five spot pattern Hele-Shaw cell was done by Mahaffey et al. (1966). They concluded that at the high mobility ratios an early breakthrough should be expected, at around 0.25-0.35PV injected. Nevertheless a reasonable sweep efficiency of 50-60% would be achieved at 1PV injected.

Earlier investigations into the impact of heterogeneities with a Hele-Shaw cell used a streamline analysis to test flow-stream distortion due to the size and shape of heterogeneities (Greenkorn et al. 1964; Kufahl & Greenkorn 1968). These studies observed that the strongest area of influence for permeability heterogeneities is across the main diagonal between injector and producer. Another study by Reed & Greenkorn (1969) examined the impact of heterogeneities by looking at the flow pattern during two-fluid viscous dominated flow and the importance of knowing the size and location of heterogeneities was highlighted, since relatively low area heterogeneity could have a big effect on the total recovery. However the study did not achieve an agreement between Hele-Shaw cell results and a porous media homolog. The overall literature review on a Hele-Shaw cell revealed that a limited amount of research has been carried out to validate a commercially used numerical simulator with a Hele-Shaw cell in order to model a first contact miscible injection in a quarter five spot pattern and specifically the impact of change in mobility ratio and heterogeneities in a horizontal 2D flow.

**Design of Hele-Shaw cell and experimental setup**

**Design and key parameters**

Most previous studies used glass plates as a base material for the Hele-Shaw cell (Greenkorn et al. 1964; Kufahl & Greenkorn 1968, Reed & Greenkorn; Mahaffey et al. 1966). There is a clear advantage of using glass, compared to some other materials, due to its higher stiffness, 65GPa for glass against 2.4GPa for polycarbonate (Bea et al. 2009). Glass is thus less likely to “sag” due to its own weight in a Hele-Shaw cell with a large surface area or suffer “doming” during the injection of high viscosity fluid. However due to manufacturing constraints the Hele-Shaw cell used in the current study was constructed using two 50x50x1.2cm polycarbonate sheets (Clear Lexan 9030), with an internal area of the cell of 40x40cm. The size of the cell was chosen in order to allow the formation of the fingers in the system and to allow us to capture the effect of macroscopic heterogeneities on the flow. A cropped 0.25mm thick PTFE sheet (Teflon) was used as a spacer to control the distance
between the plates and 0.35mm thick silicone rubber was used to seal out the fluid inside the cell. It helped to avoid using any glue in the system, which could have altered the thickness between the plates and also could contaminate the fluids.

In order to be able to constantly change heterogeneities for different runs the Hele-Shaw cell was constructed so that it could be easily dismantled and put back together. This was accomplished by using M6 size bolts placed in equally spaced holes on the outer side of the Hele-Shaw cell where the rubber is located (Fig. 1). The plates were compressed by screwing the bolts with nuts using an equal amount of torque with an automatic drill. This was performed in a diagonal manner to ensure the homogeneous distribution of the force on the rubber around the cell. This method also prevented us from having to make a thread in the polycarbonate sheets, which could have damaged them. 1/8in BSP male connections were used as an inlet and outlet for the fluid. Having an inlet on the top plate and an outlet on the bottom ensured the operation of the system at the atmospheric conditions without any backpressure at the outlet.

**Fig. 1 - Schematic of the Hele-Shaw cell design constructed using two 50×50×1.2cm polycarbonate plates.**

The average thickness between the plates was initially designed to be 0.250mm, however by reverse engineering the volume measurements of the cell the actual thickness was found to be 0.375mm. There could be two main reasons for this. One of them is “doming” of the cell in the centre due to the high surface area and another is uncertainty in the thickness of the silicone rubber and its insufficient compression. In order to quantify which of these effects was the most likely reason, the smaller model of Hele-Shaw cell was constructed with an internal area of 20×20cm, which is equivalent to 1/4 of the original area (Appendix B). The calculated internal volume of the smaller model came out to be also equivalent to 1/4 of the original Hele-Shaw cell. This suggests that most likely reason for having higher volume initially was an insufficient compression of the silicone rubber and therefore the new thickness of 0.375mm was used in further calculations. The equivalent permeability for this thickness is 11,719 Darcy.

The heterogeneities were constructed using PVC cling film (plastic food wrap). By controlling the number of layers of the PVC cling film the required thickness of the system was achieved. A square shape of 20×20cm size was used for all cases and their equivalent permeability values are listed in Table 1.

**Table 1 - Thickness of heterogeneities and equivalent permeability in the zone of heterogeneity**

<table>
<thead>
<tr>
<th>Thickness of Heterogeneity [mm]</th>
<th>0</th>
<th>0.05</th>
<th>0.12</th>
<th>0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent Calculated Permeability [Darcy]</td>
<td>11719</td>
<td>8802</td>
<td>5419</td>
<td>2552</td>
</tr>
</tbody>
</table>

**Analogue Fluid**

A mixture of glycerol with water was used as an analogue of hydrocarbon reservoir fluids and pure water was used as the displacing fluid (i.e. solvent). The choice was made based on the following criteria:

1. The solvent and reservoir fluid have to be first contact miscible.
2. The relationship between mixture viscosity and water concentration is known (Cheng 2008). This means it is easy to make a model oil of a specified viscosity as well as to model the viscosity behaviour in the simulations.
3. Previous experimental studies have shown that the properties of the analogue reservoir fluid are representative of the real reservoir fluids, such as light and heavy oil as in Alkindi et al. (2011) and Al-Hadhrami et al. (2014).

AnalaR Normapur® Glycerol bidistilled 99.5% was used in the current study. Lissamine™ Green Dye (60% content) was selected as the dyeing agent for glycerol/water mixtures. It is non-reactive with the mixture and non-adhesive to the surface of the polycarbonate sheets. By using 0.12g of dye per 200ml of glycerol/water mixture a dark blue colour of the reservoir fluid was achieved. Since the solvent and reservoir fluid are first contact miscible the endpoint relative permeability values are the same, thus simplifying the equation for mobility ratio, which becomes equivalent to viscosity ratio. **Table 2** gives the properties of the pure liquids and mixtures used in the experiments, as well as the concentrations used to achieve the required viscosity ratios at 20°C, calculated using the relationship measured by Cheng (2008).
Table 2 - Physical properties of pure glycerol, water and their mixtures for different mobility ratios at 20°C

<table>
<thead>
<tr>
<th>Density $\rho$ [kg/m$^3$]**</th>
<th>Viscosity $\mu$ [cp]**</th>
<th>Water Concentration [%]**</th>
<th>Glycerol Concentration [%]**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water</td>
<td>1000</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Mobility Ratio, M=2</td>
<td>1062</td>
<td>2</td>
<td>79.8</td>
</tr>
<tr>
<td>Mobility Ratio, M=5</td>
<td>1109</td>
<td>5</td>
<td>63.8</td>
</tr>
<tr>
<td>Mobility Ratio, M=10</td>
<td>1154</td>
<td>10</td>
<td>47.1</td>
</tr>
<tr>
<td>Mobility Ratio, M=20</td>
<td>1180</td>
<td>20</td>
<td>37.0</td>
</tr>
<tr>
<td>Mobility Ratio, M=50</td>
<td>1206</td>
<td>50</td>
<td>26.1</td>
</tr>
<tr>
<td>Mobility Ratio, M=100</td>
<td>1222</td>
<td>100</td>
<td>19.2</td>
</tr>
<tr>
<td>Pure Glycerol</td>
<td>1262</td>
<td>1413</td>
<td>0</td>
</tr>
</tbody>
</table>

*Alkindi et al. (2011)  
**Cheng (2008)

**Experimental Setup**

A schematic of the experimental setup is shown in Fig. 2. A Dual Head Constant Pressure Digital HPLC Pump (flowrate precision of ±2%) was used to inject the fluid into the Hele-Shaw cell. Controlled flowrate was preferred to controlled injection pressure in order to be able to perform effluent calculations of the recovered reservoir fluid with a better accuracy. The concentration of the recovered reservoir fluid was calculated using the weight of an effluent with known densities of both the reservoir fluid and the solvent. Two balances were used, one for monitoring and calibrating the injection at 1ml/min flowrate (since the solvent is water – a change in weight of 1g/min is equivalent to 1ml/min) and the second for effluent weight measurements. The second balance was directly connected to the computer in order to constantly record the measurements every second over the whole period of experimental run. The effluent weight measurements were recorded up to 1 pore volume injected (PVI).

Experimental studies were recorded visually using a Trust 1080p HD Webcam capturing an image once every minute, making every other picture being equivalent to 1ml of solvent injected. This again highlights the importance of monitoring the constant injection flowrate and making adjustments if needed. Another important parameter that needs to be controlled is the horizontal level of the cell. Some of the initial experiments showed that even 1° incline of the cell toward one of the sides would alter the flow due to the high density difference between the two fluids, so these experiments had to be discarded and repeated again. Finally pressure measurements were not taken due to the fact that the operating pressure is very close to atmospheric and according to initial numerical simulation runs the change was not measurable. For a further detailed procedure of the experiment please see Appendix C.

---

1. Electronic balances used to calibrate the injection flowrate of the solvent  
2. Injected solvent (i.e. water)  
3. Dual Head Constant Pressure Digital HPLC Pump  
4. Inlet valves for fluid or gas injection  
5. The Hele-Shaw cell  
6. Outlet valve on the bottom side of the Hele-Shaw cell  
7. Electronic balances connected to a computer to record an effluent measurements  
8. Computer used to store an effluent measurements and pictures from the web camera  
9. Trust 1080p HD Webcam

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![Fig. 2 - Photograph of the experimental setup with description of all parts](image-url)
Modelling numerical simulations for a Hele-Shaw cell

Model setup

The numerical simulations were carried out using the commercial simulator – Eclipse-100. It is a first order finite-difference modelling simulator and we used a fully implicit mode. A 2D (x-y) Cartesian grid was used with the same dimensions as in the experimental setup. The grid size of 400x400x1 cells was selected after the grid refinement study, which is discussed later. For input parameters no history matching was involved, since most of the parameters were quantified experimentally and input directly. The solvent and oil were modelled as two components and no gas phase was included in simulation. According to Lantz (1970) the partial differential equations that are used in numerical simulators to calculate two phase immiscible displacement are exactly the same as those for first contact miscible displacement processes, as long as the appropriate relative permeability and capillary pressure functions are used. Therefore using Eqs. 2 and 3 new relative permeability curves for numerical modelling were calculated (see Appendix D). Since glycerol/water mixture and water are first contact miscible the capillary pressure was set to zero.

\[ k_{rw} = \mu_w S_w / \mu(S_w) \]  
\[ k_{rn} = \mu_o (1 - S_w) / \mu(S_w) \]  

* Lantz (1970)

The injector was operated at a constant rate and the producer was operated at a constant bottom-hole pressure (BHP) as in the experiment. The injector and producer were placed in the same location as in the experiment and the fact that the production well is located on the bottom plate was compensated for using atmospheric BHP. Since the grid orientation effect is significant in a quarter five spot pattern, two different grid orientations were constructed. The main one included the diagonal location of the wells relative to the Cartesian grid (400x400) and the other one had wells located parallel to each other. The grid with the parallel location of the wells was constructed using a bigger 560x560 grid, but keeping the same individual grid block size. The wells in the parallel model were located at the same relative locations as in the experiment and the cells around the required area were deactivated in order to get the same size as the initial diagonal model. The area difference between diagonal and parallel models was 0.5%, which allows an accurate comparison of the results between two models. As suggested by Christie (1989) a nine-point pressure difference scheme was also used as an alternative to the standard five-point. The study was carried out to compare the two methods and it revealed that using five-point pressure difference method could not produce representative flow behaviour in simulation of quarter five spot pattern injection, especially in the fine grid models (Appendix E). Heterogeneity zones were modelled by multiplying the permeability of the cells in that zone by the fraction of the permeability that it represents compared to the initial value, for instance a 0.12mm heterogeneity zone permeability by (5,419[D]÷11,719[D])=0.46. Using a specific porosity value for each thickness compensated for the change in the capacity of the specific heterogeneity zone. (For a full data file please see Appendix F)

The colour map interpolation methods used to illustrate the saturation maps of the simulation results were carefully chosen. For the initial grid refinement, grid orientation and random permeability studies the HSV interpolation method was chosen because it uses a wider range of colours. This ensured a better resolution to see the effect of numerical dispersion. In order to compare saturation maps of a simulation runs that were replicating experimental conditions the RGB interpolation method was preferred. It better represents the actual physical change in colours between white and dark blue, with change in concentration.

Population of the model with random permeability

One of the challenges of modelling unfavourable displacements during miscible injection is to trigger the formation of viscous fingers. Using a fully homogeneous model would not correctly represent the behaviour of finger formation and therefore the application of a random permeability field is required. This could be done either by use of a random permeability box around the injector or to populate the whole grid with the random permeability values. The first option is often applicable during line drive pattern modelling, but in a quarter five spot pattern fingers tend to smooth out as soon as they leave the area of the random permeability box. This happens because of the grid orientation effect and so in this case the method of applying random permeability over the whole grid works better.

A separate study was carried out to examine what range of random permeability values is required to trigger fine enough fingers that represent experimental behaviour. A mobility ratio of M=20 was used for this study to ensure that a good resolution of the viscous fingers at higher viscosity ratios would be achieved. This was done as an iterative process together with the grid refinement study and so the final study was carried out on the finest grid (400x400), which was used for all further simulations. The random permeability numbers were generated using Microsoft Excel. It has a “RANDBETWEEN” function which uses a uniform distribution to generate random numbers. The calculated permeability of the system (11,719 [D]) was chosen as the average value of the uniform distribution. This ensured conservation of average permeability for the whole model as in the experimental setup. Variations in permeability of ±0%, ±10%, ±20%, ±30%, and ±40% were applied. Ideally to carry out a proper statistical analysis of the impact of randomly generated permeability values a large set of outcomes would be required. However, due to the time constraints, for each of the range variations 10 different randomly generated permeability grids were used. This ensured that the aspect of randomness of the results was quantified at least in a simplified manner.

The results of the study revealed that having a model with randomly generated permeability values clearly introduces a variation in the outcome of the results for both total oil production and breakthrough time. In the case of total production it can be seen in Fig. 3a that it falls considerably compared to the homogeneous grid. However increasing the range of the random
permeability further, does not change the range of variation of the results considerably and it stays relatively constant in the range of 7-10%. The breakthrough time also do not vary significantly with increasing randomness variation as well, being in the range of 4-9% (Fig. 3b). These results suggest that the best way to choose the required range of random permeability is by a visual analysis of fingers formation in different cases for numerical simulations. Fig. 4 shows that the homogeneous model has a very unnatural flow pattern and permeability variations of 30% and more produce more realistic fingering pattern. Therefore the best 30% variation in random permeability was used for further studies.

![Fig. 3 - Variation in the results for different parameters at 1PVI with the introduction of different ranges of random permeability values populated over the whole grid using 400×400 grid size and M=20](image)

(a) Range of the results for total oil production. (b) Range of the results for a breakthrough time

![Fig. 4 - Oil saturation maps for the different ranges of randomly generated permeability values generated by numerical simulations using 400×400 grid size and M=20 at 0.25PVI.](image)

Grid refinement and grid orientation study

A study was performed to investigate the impact of grid refinement using the results from variability in the random permeability distribution (needed to initiate viscous fingering) study. The permeability of each grid block was selected at random with an allowable range 30% of the measured permeability. Ten different realisations were created on grid sizes of 10×10, 60×60, 100×100, 200×200, and 400×400 grid cells. Simulations were then performed on all these models using a mobility ratio of M=20 and the ranges of recoveries and breakthrough times analysed. It should be noted that most grid refinement studies do not include the impact of uncertainty in the permeability distribution on the results.

By having more cells with a random permeability value one would expect to have a wider spread of results due to the extra complexity in the system. Nevertheless the results in Fig. 5a and 5b show that for a finer grid resolution the range of the results for both oil production and breakthrough time does not significantly change, being in the range of 4-9%. Fig. 7a also shows that we get convergence of results for oil production at 400×400 grid resolution, while for breakthrough time full convergence was not achieved (Fig. 7b). Qualitative analysis also clearly indicates the need for having a fine 400×400 grid in order to have a good resolution of viscous fingering (Fig. 6).

Using a nine-point pressure difference method reduced the impact of grid orientation (Appendix E), yet the impact is still considerable for parallel grid model, both in terms of the flow pattern and results. Fig. 6 shows that for parallel grid orientation the flow pattern is still strongly concentrated across the main diagonal between the wells and the effect of viscous fingering is not as large as it would be expected for a relatively high mobility ratio of M=20. Also Fig. 5a and 5b show that parallel grid leads to an earlier breakthrough and lower total recover. This show that results by Yanosik and McCracken (1979) do not apply to the case for the grid with random permeability values, since the difference between two orientations could be in the range between 0-10.6%, which is bigger uncertainty range than predicted 1.5%. The most optimal result should be in-between parallel and diagonal grids, but because diagonal grid allows more fingers to develop, it was used for further comparative analysis.
Experimental and Numerical Studies of First Contact Miscible Injection in a Quarter Five Spot Pattern

Fig. 5 - Variation in the results for different parameters at 1PVI with the change in grid size and orientation using 30% variation in random permeability, 400×400 grid size and M=20 (a) Range of the results for the total oil production. (b) Range of the results for the breakthrough time. (Using nine-point pressure difference scheme)

Fig. 6 - Oil saturation maps for the different grid sizes and orientations using 30% variation in random permeability, 400×400 grid size and M=20 at 0.25PVI. (Using nine-point pressure difference scheme)

Fig. 7 - Change of the parameters with increasing numbers of cells in numerical model simulated using 30% variation in random permeability, 400×400 grid size and M=20. (a) Results for the total oil recovery. (b) Results for the breakthrough time. (Using nine-point pressure difference scheme)
Analysis and discussion of numerical and experimental results

Analysis approach and uncertainties involved

Processing of the experimental data proved to be challenging due to the major instability of results in the early part of experimental runs. The instability involved production of a higher volume of reservoir fluid than solvent injected, which is clearly incorrect. The most likely reason is doming of the plates of the Hele-Shaw cell caused during filling of the cell with high viscosity glycerol mixtures, resulting in an increase in the volume and pressure in the cell. Since the Hele-Shaw cell was filled at an inclined angle to ensure a uniform displacement, the higher pressure was applied. This possibly caused doming in the middle of the cell due to the stiffness of the material not being high enough to prevent it. As explained earlier this could be prevented using a material with higher stiffness, such as glass. To account for this effect the results for the first five minutes of each run were discarded for effluent measurements until the system was able to reach a steady state flow.

The effluent measurements for the Hele-Shaw cell with heterogeneities were not used at all. This is due to the fact that small bubbles trapped between the layers of heterogeneity prevented uniform recovery. However it did not impact the actual flow pattern and therefore other two parameters were used to compare the results.

For the experimental results a measurement of the breakthrough time was carried out by visual analysis and the short range of possible breakthrough time was selected for each case. These uncertainties were accounted for during the later comparison of the results. In the case of the simulation results breakthrough time was specified at the point when more than 0.01ml of solvent was produced. The reason for choosing this particular number is that for all cases it was the point at which a considerable increase in water production started.

Sweep efficiency was calculated using a simplified colorimetry method for both experimental and numerical simulation results. Paint.NET digital software was used to measure the area of the cells swept by solvent relative to the total area of the cell. Because the physical dispersion is relatively low and by 1PVI the displacement front tends to smoothen out viscous fingers at all mobility ratios, this method had relatively low uncertainty in areal sweep calculations. In order to quantify the uncertainty of this method a sweep efficiency calculated by the application was compared to the actual recovery results for homogeneous simulations. It demonstrated the accuracy of the method, since the uncertainty is in the range of 0.5-2%.

Mobility ratio variation study

Quantitative analysis of both experimental and numerical simulation results showed that with increasing mobility ratio all performance parameters decrease, we get lower areal sweep and lower total oil recovery, as well as earlier breakthrough. This trend has been seen before and agrees with the observations made by Mahaffey et al. (1966). Fig. 8 illustrates the results for effluent analysis from experimental runs combined with the numerical simulation results. As was mentioned earlier, due to the excessive instability of the effluent production rate during higher mobility ratio injections the experimental results for M=50 and M=100 are not included. For M=2 and M=10 the numerical simulation results seem to be overestimating total recovery. While for M=5 and M=20 there is initial disagreement between the results which is followed by the convergence in the recovery results at 1PVI. No particular pattern could be seen and in some cases results disagree with the fact that recovery time should be lower as mobility ratio increase. The total recovery for M=20 is higher than for M=10, although it should be vice-versa. These findings suggest that the current method of effluent measurements needs to be improved. Because of the low pore volume of the Hele-Shaw cell, currently the uncertainty in effluent calculations is relatively high compared to the areal sweep calculations. This high uncertainty could be reduced if the total time of the experimental runs were made longer by reducing the injection flowrate. Another important suggestion for improvement is to use a stiffer material for plates in the Hele-Shaw cell, for instance, glass.

Fig. 8 - Oil recovery results for numerical simulation at different injection mobility ratios of M=2, 5, 10, 20, 50 and 100, compared to the processed effluent measurement from experimental runs in a Hele-Shaw cell for M=2, 5, 10, and 20.
Comparison of the areal sweep results between experiments and numerical simulations showed that in general the simulation predictions gave a better recovery and areal sweep as illustrated in Fig. 9a. As the mobility ratio increases the overestimation of areal sweep increases as well and the results diverge even more. This could be happening because of the grid orientation effect in the diagonal grid. However even by carrying out the same study on the parallel grid, it did not reduce the difference enough to match the experimental data. It also had another disadvantage of concentrating the flow across the main diagonal of the flow, without having any expected viscous fingering at high mobility ratios as observed in the experimental results. (Appendix G).

Using a nine point pressure difference method did indeed reduce the impact of the grid orientation effect, nevertheless it illustrated that by trying to predict the flow pattern of unstable flow the simulator tends to overestimate the results of the areal sweep. In order to see if the quantitative results between two methods could be matched at any cost another study was carried out and it included simulations on a parallel grid using the initial five-point pressure difference scheme. It was certainly expected that this method would present very poor areal sweep pattern results. It revealed that by switching back to the five-point pressure difference the disagreement between the results increases even more. The opposite impact is observed in this case because by increasing the mobility ratio of injection the numerical simulations tend to underestimate the areal sweep and the flow pattern seems completely unphysical with flow occurring mainly along the main diagonal. (Appendix G)

Even though there is disagreement between the results for an areal sweep, the breakthrough times are generally within the uncertainty limits for all cases. As illustrated in Fig. 9b the spread between numerical simulations and experimental results is not as high as for the areal sweep results in Fig. 9a. Most of the results either are in agreement or at least within a small range. The only exception is for mobility ratio M=2, where there is a large difference between the experimental and numerical simulation results. However it could have been caused by some experimental error, because the flow pattern is very close to the one at M=5. Therefore it would be reasonable to rerun this particular experimental case if there was more time.

![Fig. 9 - Comparison of results between the numerical simulation and experimental runs carried out in a homogeneous model by mobility ratios. (a) Areal sweep. (b) Breakthrough time. Uncertainties for simulations are based on the initial study into the impact of random permeability application over the whole grid. Uncertainties for areal sweep in experiments are based on the study into the accuracy of colorimetry method and for breakthrough time based on the visual observations. All uncertainties are shown with error bars](image)

In terms of the qualitative analysis of the results a good agreement is achieved for the general areal sweep pattern between experimental and numerical results up to a certain mobility ratio as it can be seen in Fig. 10a through 10d. Nevertheless in the numerical simulations the size of viscous fingers is much bigger than in the experiments (Fig. 10a through 10d). Even though the grid is already of a very high resolution, it could be one of the reasons for this difference. Also at high mobility ratios the impact of grid orientation could be clearly noticed. At M=50 and M=100 it can be seen in Fig 10c and 10f that a higher number of major viscous fingers form at the earlier stages of an injection, two in the simulations instead of one in the experimental runs. The orientation of these fingers in simulations is initially concentrated in X and Y directions compared to the diagonal in the experiments. Even though a nine-point pressure difference scheme was used, some residual impact of grid orientation is still present. This could be one of the explanations for having a better sweep in simulations at higher mobility ratios. Fig. 10g and 10h shows that after breakthrough occurs through a longer finger in simulation the other major viscous fingers that did not reach a producer tend to join to the main stream by sweeping the area in between them.

A general conclusion for the mobility ratio study is that the numerical simulations overestimate the oil production and areal sweep. With increasing mobility ratio the variability in recovery also increases. None of the implemented methods are able to exactly match the results in terms of qualitatively reproducing the observed flow pattern. Nevertheless there is a smaller spread of results in breakthrough times, which indicates a validity of this method for predicting it. This study again highlights that it is challenging to model miscible injection in a quarter five spot pattern. However at moderate mobility ratios simulation could be used if the level of uncertainty would be accounted for.
Experimental and Numerical Studies of First Contact Miscible Injection in a Quarter Five Spot Pattern

Fig. 10 - Comparison of the oil saturation maps between experimental runs and numerical simulations in a homogeneous model. (a) M=2 at 0.25PVI (b) M=5 at 0.25PVI (c) M=10 at 0.25PVI (d) M=20 at 0.25PVI (e) M=50 at 0.15PVI (f) M=100 at 0.15PVI (g) M=50 at 0.50PVI (h) M=100 at 0.50PVI
**Heterogeneity: Impact of thickness**

Additional studies were carried out to investigate the impact of heterogeneities on the areal sweep and breakthrough time. In this part permeability heterogeneities with a size of 20×20cm and varying thickness were placed in the centre of the cell. As in the studies with a homogeneous Hele-Shaw cell the numerical simulation overestimated areal sweep compared to the experimental runs (Fig. 11a). However for 0.05mm and 0.20mm thick heterogeneities the difference between two analogues decreased compared to the homogeneous model. This happened due to the fact that for these thicknesses numerical simulation did not show any increase in production from the homogeneous model, while in the experimental results as much as 10% of incremental production was added. The same increase was observed in the experimental run with a 0.12mm thick heterogeneity, yet because of the equivalent increase in areal sweep for numerical simulation, the difference between the two stayed similar.

The increase in areal sweep for the experiments with the higher permeability heterogeneity (0.05mm thick) could be explained by the fact that for numerical simulations these zones were more easily penetrated and by having an earlier breakthrough the extra water production did not allow additional sweep around the heterogeneity as seen in the experiments (Fig. 11b). While for a 0.20mm thick heterogeneity the decrease in difference between numerical simulation and experimental results is due to the heterogeneity not being penetrated by solvent, which thus helped to match a grid orientation effect by directing the flow around it. Another pattern that could be noticed is that for experiments the breakthrough time is delayed as the thickness of heterogeneities decreased. However this did not impact on the total areal sweep at 1PVI for all experimental cases because of the lower incremental sweep after later breakthrough.

As for the qualitative analysis of the results it was already mentioned that in numerical simulations the solvent easily passes through the heterogeneity zone. Especially in the case of 0.05mm the impact of heterogeneity is barely noticeable, as if there is no heterogeneity in the zone at all (Fig. 12a and 12b). At the same time in case of 0.20mm heterogeneity the solvent did not enter the this zone, while in numerical simulator some penetration could be noticed (Fig. 12d). It is possible that this was due to a different wettability of the PVC cling film compared with the polycarbonate, however further investigations suggested that both materials are water wet. Another reason could be increased thickness of heterogeneity due to the air bubbles trapped between the layers of heterogeneity. This suggests that either some other physical aspects are not considered in the numerical simulation, or the permeability (i.e. thickness) for this particular case was not predicted accurately enough.

![Fig. 11](image-url)

**Fig. 11** - Comparison of the results for numerical simulation and experimental runs with different thicknesses of 20×20cm heterogeneity in the centre of the model. (a) Areal sweep results. (b) Breakthrough time results. Uncertainties for simulations are based on the initial study into the impact of random permeability application over the whole grid. Uncertainties for areal sweep in experiments are based on the study into the accuracy of colorimetry method and for breakthrough time based on the visual observations. All uncertainties are shown with error bars.
Experimental and Numerical Studies of First Contact Miscible Injection in a Quarter Five Spot Pattern

(a) Homogeneous model \( (k=11,719 \text{ Darcy}) \)
(b) 0.05mm Heterogeneity \( (k=8,802 \text{ Darcy}) \)
(c) 0.12mm Heterogeneity \( (k=5,419 \text{ Darcy}) \)
(d) 0.20mm Heterogeneity \( (k=2,552 \text{ Darcy}) \)

Fig. 12 - Comparison of the oil saturation maps between experimental runs and numerical simulations with a different thicknesses of 20×20cm heterogeneity in the centre of the model at 0.50PVI. (a) Homogeneous model. (b) 0.05mm heterogeneity. (c) 0.12mm heterogeneity. (d) 0.20mm heterogeneity

Heterogeneity: Impact of location

A heterogeneity box of 0.12mm thickness was used to investigate the impact of the location of heterogeneity on the areal sweep and breakthrough time. The locations were varied across the main diagonal, having them in the following locations: close to the injector (5cm from top and 5cm from left side), in the centre of the Hele-Shaw cell, close to the producer (5cm from bottom, 5cm from right side) and also on the side of the main diagonal (5cm from bottom, 5cm from left side). The results for numerical simulations did not show any increase in areal sweep by moving the heterogeneity either closer to the injector or producer (Fig. 13a). However for experiments we can see a highest incremental increase in areal sweep for the heterogeneity close to the injector. An increase is 8% higher than for heterogeneities in the centre or near producer, with a better 16% sweep compared to the initial homogeneous model. Therefore having heterogeneity close to the injector decreases the difference between the experiments and numerical simulations. This is because the heterogeneity diverts the flow the way as the grid orientation error in the diagonal grid, similarly to the earlier observation of 0.20mm thick heterogeneity.

For the heterogeneity on the side of the main diagonal simulation and experimental results disagree in terms of the change relative to the homogeneous model. For numerical simulation having heterogeneity on the side decreases areal sweep compared to the heterogeneity in the centre of the cell, while for the experiments the heterogeneity on the side increases the incremental areal sweep. This effect can be seen in Fig. 14d, where the solvent sweeps the large area on the opposite side of the heterogeneity location, at the same time leaving a big shadow zone downstream of it, which is eventually swept at later time. In the numerical simulation for the same case no shadow zone can be observed at all, since the solvent enters the heterogeneity. This decreases the difference between quantitative results of numerical simulation and experiments. However this agreement of recovery is fortuitous and requires more studies using a Hele-Shaw cell to make any conclusions.

For the visual sweep pattern of the penetration of heterogeneity zone the closest match is observed for the case with heterogeneity close to the injector. This also explains the close match for experimental and numerical simulation areal sweep results of the same case. In general implementation of heterogeneity equivalent to around a half of the original permeability and ¼ of the size of the system in any of the locations improve the areal sweep for both numerical simulation and experiments, compared to the homogeneous model. The breakthrough times are within the uncertainty range for all experimental runs and numerical simulations (Fig. 13b). This is an important observation for further real life use of these results. On the one hand this means the simulation is ‘safe’ to use for field scale cases as we are less concerned about predicting where the solvent goes, unless we want to drill an infill well or estimate the effectiveness of conformance control (e.g. foam injection). While on the other hand if the simulator cannot predict the location of the solvent in a simple case, how confident can we be that it will be
Experimental and Numerical Studies of First Contact Miscible Injection in a Quarter Five Spot Pattern

Correct in more realistic heterogeneities? Therefore the decision to rely on the results from simulation is to be made based on the specific needs and level of uncertainty one can afford in terms of the areal sweep pattern.

Fig. 13 - Comparison of the results for numerical simulation and experimental runs with different locations of 20×20 cm heterogeneity of 0.12 mm thickness. (a) Areal sweep results. (b) Breakthrough time results. Uncertainties for simulations are based on the initial study into the impact of random permeability application over the whole grid. Uncertainties for areal sweep in experiments are based on the study into the accuracy of colorimetry method and for breakthrough time based on the visual observations. All uncertainties are shown with error bars.

(a) Heterogeneity near Injector
(b) Heterogeneity in the Centre
(c) Heterogeneity near Producer
(d) Heterogeneity on the Side

Heterogeneity: Impact of orientation

The impact of the orientation of a 20 cm×20 cm square heterogeneity in the centre of the cell was also investigated for two different thicknesses, 0.12 mm and 0.20 mm, which are equivalent to 5,400 D and 2,600 D. The heterogeneity box was rotated by 45° degrees, having the flat face perpendicular to the main diagonal of the flow. Quantitatively there was almost no difference between the results from the two different thicknesses in terms of the areal sweep and breakthrough time (Fig. 15a and 15b).
In the case of the 0.12mm heterogeneity having a flat face perpendicular to the main diagonal of the flow increased areal sweep for both numerical simulation and experiment. For the experimental case an incremental production for the rotated heterogeneity is achieved, but with the cost of having an earlier breakthrough (Fig. 15b).

The main observation by qualitative analysis in the experimental results was that for the cases with the rotated heterogeneity a shadow zone was observed downstream of the heterogeneity (Fig. 16b and 16d). This is especially well highlighted in Fig. 16d, where some of the reservoir fluid left unswept even though permeability in that zone is the same as in surrounding area. However this is a temporary effect, because at higher PVI these zones are eventually swept. In general varying the orientation of the square box did not impact the differences between numerical simulations and experiments.
Summary and Conclusions

We have investigated the impact of mobility ratio and heterogeneities on total oil recovery, areal sweep and breakthrough time during a miscible injection in a quarter five spot pattern. We used two 2D horizontal analogues of flow in porous media. Numerical simulations were conducted using the Eclipse-100 simulator and experiments were carried out using a horizontal Hele-Shaw cell. Well-defined heterogeneities were implemented in the experimental setup using a relationship derived by Greenkorn (1964) to calculate the permeability in the Hele-Shaw cell. The impact of thickness, location and orientation of the square box heterogeneity was studied.

In order to overcome the challenges for numerical modelling of miscible injection in a quarter five spot pattern that were highlighted by Christie (1989) and Fayers (1987), a nine-point pressure difference scheme was used, together with the random permeability values across the whole grid. The average of these random permeability values was the corresponding permeability calculated for the Hele-Shaw cell. The impact of changing the realisation of the random permeability distribution was investigated by running ten cases for each grid size and random permeability range. The study revealed that having a random permeability adds an uncertainty in the final results in the range of 7-10% for the oil recovery and areal sweep at 1PVI, and 4-9% for the breakthrough time.

Our results into the impact of viscosity ratio on areal sweep in a homogeneous quarter five spot are consistent with those presented by Mahaffey et al. (1966) on a fully homogeneous experimental model. A good agreement was achieved for breakthrough times for both experimental runs and numerical simulations, however this was not the case for the areal sweep results, since it was observed that numerical simulations tend to overestimate the areal sweep. The difference between the areal sweep results for the two methods increases with the increased mobility ratio. This is mainly due to the grid orientation effect resulting in formation of extra major viscous fingers in numerical simulations. Several methods were implemented in order to try to reduce the effect between experimental and simulation results, such as using a parallel grid or switching back to five-point pressure difference scheme. None of them proved to be solutions for this problem. Qualitative results demonstrated that high-resolution numerical simulation is able to relatively accurately match flow pattern for the miscible displacement in a quarter five spot pattern at lower mobility ratios. However to match the size of the viscous fingers finer grid resolution might be required.

For the study on the impact of heterogeneities it was observed that in general the application of any type of square permeability heterogeneity across the main diagonal of the flow between the injector and producer would improve the areal sweep compared to the homogeneous model. However in some cases this might be achieved with the cost of an earlier breakthrough. In general numerical simulations were not able to accurately predict the behaviour of the flow with introduction of heterogeneity compared to the experimental runs. Most of the inaccuracies were caused by more extensive penetration of the heterogeneity zone and not being able to accurately represent the shadowing zones around the heterogeneities. At the same time one of the other important observations was that locating heterogeneity closer to the injector achieved a higher areal sweep than for the other cases also matching the grid orientation effect that occurs in numerical simulation. The study of the impact of the thickness of heterogeneity showed a different level of penetration of heterogeneity between experimental runs and numerical simulations than in other cases. In the case of the orientation of square heterogeneity it was found that having a flat face perpendicular to the main diagonal of the flow improves the areal sweep at 0.12mm heterogeneity with the cost of an earlier breakthrough, while for a thicker heterogeneity the difference is insignificant. Finally the most unexpected observation was made by placing the heterogeneity on the side of the main diagonal of the flow. With heterogeneity in that area the areal sweep result was almost as high as in the case with heterogeneity close to the producer. This was achieved because of the big shadow zone that was formed near heterogeneity that was eventually swept at higher PVI. However this observation is fortuitous and requires more studies using a Hele-Shaw cell to be validated.

The general conclusion for the study is that the Eclipse-100 numerical simulator is able to model the miscible injection in a quarter five spot pattern in a 2D system without gravity within an acceptable uncertainty range at lower mobility ratios (M=2 to M=10), although at higher mobility ratios (M=50 and M=100) some new solutions are needed to reduce the grid orientation effect, which leads to an overestimation of the results. Nevertheless at M=20 the introduction of heterogeneities reduces the discrepancy between experimental and simulation results, and brings it back within uncertainty limits in some of the cases. However this is mostly achieved due to the fact that certain heterogeneities compensate for the grid orientation effect by directing the flow around the heterogeneity box. This suggests that if an area of heterogeneity is small or it is close to a producer, it will not counteract for the grid orientation effect, because flow will not be spread enough. In terms of the breakthrough times a good agreement was observed between numerical and experimental results at all mobility ratios. This shows that simulations could be used as a valid tool for some field scale studies where breakthrough time is of more concern rather than sweep pattern. One of the other important goals of this project that was achieved is to design and construct an experimental setup that could be used for an academic demonstration purposes.

Suggestions for further improvement and research

It was already mentioned earlier that the results from this study could be used for a further research. We have demonstrated the possibility of modelling a miscible injection using a simple numerical simulation within acceptable uncertainty range for certain cases. This means that we could use the same model for a field scale studies by implementing some of the key empirical fractional flow models for miscible injection discussed earlier. This will allow engineer to simulate some of the conditions which could not otherwise be simulated in field scale models because of the need for a large number of
grid blocks to capture the viscous fingering. At the same time it would be useful to compare the results of this study to analytical solutions and streamline simulations as appropriate.

For an improvement of the experimental setup the most important suggestions are to use a stiffer material for the plates in the Hele-Shaw cell and try to run experiments at a lower flowrate over a longer time period in order to achieve more stable effluent measurements. At the same time to achieve stability in effluent measurements in heterogeneous models it is better to use a different material for heterogeneity construction, which would not require layering, because air bubbles trapped in between them could obstruct effluent collection. In case if the glass would be used as the base material the heterogeneities could be indent in it. This will ensure a better accuracy of the measurements.

**Nomenclature**

- \( h \) = space between plates [m]
- \( k \) = permeability [mD]
- \( M \) = mobility ratio
- \( \mu \) = viscosity [cp]
- \( S_w \) = water saturation [fraction]

**Abbreviations**

- BHP - Bottom Hole Pressure
- PSP - Pore Space Pressure
- HSV - Hue/Saturation/Value
- PTFE - Polytetrafluoroethylene (Teflon)
- PVI - Pore Volume Injected
- RGB - Red/Green/Blue

**References**


## Appendix A: Critical literature review and Milestones

### MILESTONES OF EXPERIMENTAL AND NUMERICAL STUDIES OF FIRST CONTACT MISCIBLE INJECTION IN A QUARTER FIVE SPOT PATTERN

#### TABLE OF CONTENT

<table>
<thead>
<tr>
<th>SPE Paper No</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>999</td>
<td>1964</td>
<td>“Flow in Heterogeneous Hele-Shaw Models”</td>
<td>R.A. Greenkorn, R.E. Haring, H.O. Jahns, and L.K. Shallenberger</td>
<td>First study to illustrate the analogy between the flow in Hele-Shaw models and in porous media. As well as proved that Hele-Shaw cell could be used as an analogue to the flow in porous media to study the impact of heterogeneities on the flow.</td>
</tr>
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<td>1966</td>
<td>“Sweep Efficiency by Miscible Displacement in a Five-Spot”</td>
<td>J.L. Mahaffey, W.M. Rutherford, C.S. Matthews</td>
<td>First study to investigate breakthrough time and areal sweep during a miscible injection at high mobility ratios in homogeneous Hele-Shaw cell.</td>
</tr>
<tr>
<td>2433</td>
<td>1968</td>
<td>“The Effect of Heterogeneity on Single Phase Flow in Porous Media”</td>
<td>R.H. Kufahl, R.A. Greenkorn</td>
<td>First study to quantify the impact of different arrangements of heterogeneities in a Hele-Shaw cell on the total oil recovery and breakthrough time.</td>
</tr>
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<td>1968</td>
<td>“The Effect of Heterogeneity on Two-Fluid Viscous-Dominated Flow in Porous Media”</td>
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<td>First study to investigate the impact of higher permeability heterogeneity on the breakthrough time and areal sweep results.</td>
</tr>
<tr>
<td>5734</td>
<td>1979</td>
<td>“A Nine-Point, Finite-Difference Reservoir Simulator for Realistic Prediction of Adverse Mobility Ratio Displacements”</td>
<td>J.L. Yanosik, T.A. McCracken</td>
<td>First to carry out the study on the impact of grid orientation by using a nine-point pressure difference scheme instead of standard five-point in a finite difference reservoir simulator.</td>
</tr>
<tr>
<td>NSOGR*</td>
<td>1987</td>
<td>“A review of the status of computation for evaluating miscible flood performance”</td>
<td>F.J. Fayers</td>
<td>Discussed some of the general considerations that need to be taken into account for numerical modelling of miscible injection in a quarter five spot pattern.</td>
</tr>
<tr>
<td>16005</td>
<td>1989</td>
<td>“High-Resolution Simulation of Unstable Flows in Porous Media”</td>
<td>M.A. Christie</td>
<td>Discussed some of the methods for triggering formation are investigated. Also providing the general idea on the range of random permeability values need to be used.</td>
</tr>
</tbody>
</table>

*From North Sea Oil and Gas Reservoirs. Chap 17, 231-244. Graham and Trotman Ltd.
SPE-999-PA (1964)
Flow in Heterogeneous Hele-Shaw models

Authors: Greenkorn, R.A., Haring, R.E., Jahns, H. O., Shallenberger, L. K.

Contribution to understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):

First study to illustrate the analogy between the flow in Hele-Shaw models and in porous media. As well as proved that Hele-Shaw cell could be used as an analogue to the flow in porous media to study the impact of heterogeneities on the flow.

Objective of the paper:

The objective of the paper is to study the impact of heterogeneities on the flow in porous media using Hele-Shaw cell as an analogue.

Methodology used:

Impact of size, level and shape of heterogeneities on the flow stream distortion was studied using streamline analysis.

Conclusions reached:

The experimental data showed a good agreement with numerical results and analytical solutions. Size and level of heterogeneity has a bigger impact on the flow than the shape, as long as the heterogeneity is not long and narrow.

Comments:

Displacement front patterns were not addressed.

SPE-1233-PA (1966)

Sweep Efficiency by Miscible Displacement in a Five Spot

Authors: Mahaffey, J.L., Rutherford, W.M., Matthews, C.S

Contribution to understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):

First study to investigate breakthrough time and areal sweep during a miscible injection at high mobility ratios in a homogeneous Hele-Shaw cell.

Objective of the paper:

To study the displacement behavior of miscible injection in a porous media using a Hele-Shaw cell as an analogue.

Methodology used:

12in. square Hele-Shaw cell of a completely developed five spot pattern was used. Spacing between the plates was 0.0047in. Glass plates were used as a base material for Hele-Shaw cell.

Conclusions reached:

It was concluded that at the high mobility ratios the early breakthrough should be expected at around 0.25-0.35PV injected. Nevertheless a reasonable sweep efficiency of 50-60% would be achieved at 1PV injected.

Comments:

Results were not compared to either numerical simulations or analytical solutions.
**SPE-2433-MS (1968)**

The Effect of Heterogeneity on Single-Phase Flow in Porous Media.

**Authors:** Kufahl, R. H., & Greenkorn, R.A

*Contribution to understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):*

First study to quantify the impact of different arrangements of heterogeneities in a Hele-Shaw cell on the total oil recovery and breakthrough time.

**Objective of the paper:**
To understand the impact of heterogeneities on the flow in porous media by obtaining a phenomenological data during flow.

**Methodology used:**
Single phase displacements were studied using 12in. square, horizontal Hele-Shaw cell with the spacing between the plates of 0.0625in. A number of small circle heterogeneities were used to study their impact on the flow. Streamline distortions due to heterogeneities were investigated.

**Conclusions reached:**
A number of smaller heterogeneities could be replaced by one at different location to give same results. The heterogeneous models had about 15% earlier breakthrough compared to the homogeneous ones. The total recovery at 1PV injected is similar for almost all heterogeneity arrangements. Highlighted the possibility of using heterogeneities to advantage the flow.

**Comments:**
Poor quality of the images since the paper is relatively old.

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**SPE-2442-MS (1969)**

The Effect of Heterogeneity on Two-Fluid Viscous-Dominated Flow in Porous Media.

**Authors:** Reed, P.E., Greenkorn, R.A.

*Contribution to understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):*

First study to investigate the impact of higher permeability heterogeneity on the breakthrough time and areal sweep results.

**Objective of the paper:**
To study whether at high viscosity ratios the impact of heterogeneities on the areal sweep efficiency would be significant.

**Methodology used:**
Using a Hele-Shaw in a quarter five spot patter by placing heterogeneities in the size of around 6% of the internal area of the cell. Four different mobility ratios were investigated: M=1, 9, 46 and 112.

**Conclusions reached:**
In the case with the highest number of high permeability heterogeneities used the recovery at the breakthrough was reduced by up to 16%. The importance of knowing the size and location of heterogeneities was highlighted.

**Comments:**
Lower permeability heterogeneities were not investigated in this study.
SPE-2594-PA (1970)

Rigorous Calculation of Miscible Displacement Using Immiscible Reservoir Simulators.

Authors: Lantz, R. B.

Contribution to understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):

First paper to derive relative permeability equations that allow modelling miscible injection using immiscible reservoir simulators.

Objective of the paper:

To show that two dimensional, two-phase immiscible reservoir simulators can model miscible injection with some restrictions.

Methodology used:

First a correspondence between the sets of partial differential equations describing a displacement processes in porous media was established. Then it was studied what the finite difference of immiscible equations means in terms of the finite difference of miscible equations. Finally numerical diffusion with representative diffusion levels was compared.

Conclusions reached:

The partial differential equations that are used in numerical simulators to calculate two phase immiscible displacement are exactly the same as those for first contact miscible displacement processes, making sure that the appropriate relative permeability and capillary pressure functions are used. Equations are as follows:

\[
k_{rw} = \frac{\mu_w S_w}{\mu(S_w)}
\]

\[
k_{rn} = \frac{\mu_n (1 - S_w)}{\mu(S_w)}
\]

Comments:

There is a limitation of possibly having a truncation error.

SPE-5734-PA (1979)

A Nine-Point, Finite-Difference Reservoir Simulator for Realistic Prediction of Adverse Mobility Ratio Displacements.

Authors: Yanosik, J.L. McCracken, T.A.

Contribution to understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):

First to carry out the study on the impact of grid orientation by using a nine-point pressure difference scheme instead of standard five-point in a finite difference reservoir simulator.

Objective of the paper:

To study the difference between using a standard five-point and nine-point pressure difference schemes in numerical modelling of miscible injection.

Methodology used:

Two different grid with were constructed - diagonal with a grid size of 21×21 and parallel grid with a size of 29×29 cells.

Conclusions reached:

The maximum difference in oil recovery curves is 1.5% between diagonal and parallel arrangement of grids using nine-point a pressure difference scheme in quarter five spot pattern

Comments:

The study was carried out on a fully homogeneous grid without evidence of expected viscous fingering behavior at higher mobility ratios.
North Sea oil and gas reservoirs 1987

A review of the status of computation for evaluating miscible flood performance

Authors: Fayers, F.J.

Contribution to the understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):

Highlights some of the general considerations that need to be taken into account for numerical modelling of miscible injection in a quarter five spot pattern. Highlight some of the numerical challenges that may arise with a grid orientation effect.

Objective of the paper:

The paper reviews different methods to predict the performance of the miscible injection, at the same time highlighting some of the principal phenomena that needs to be considered.

Methodology used:

Reviewed the behavior of some of the important processes during the miscible injection. Such as viscous fingering, gravitational effect and effect of water saturation. Also discussed some of the numerical simulation setup aspects, for instance grid size and grid orientation selection.

Conclusions reached:

The was no specific conclusion reached since suggestions on the miscible injection modelling would depend on whether field secondary production of particular field is based on a pattern flooding scheme, or on peripheral edge drive. In general a flooding scheme in a certain pattern is easier to evaluate due to the uniform pressure distribution across the field.

Comments:

Paper did not discuss a method for triggering of viscous fingering in a quarter five spot pattern, only compared homogeneous numerical simulation models.

SPE-16005-PA (1989)

High-Resolution Simulation of Unstable Flows in Porous Media.

Authors: Christie, M.A.

Contribution to understanding a miscible injection process in a quarter five spot pattern (Either for numerical simulation or experimental runs in a Hele-Shaw cell):

Some of the methods for triggering formation are investigated. Also providing the general idea on the range of random permeability values need to be used.

Objective of the paper:

To describe accurate numerical methods used in order to model high resolution numerical simulation with clearly visible viscous fingering effects for both miscible and immiscible displacements.

Methodology used:

To obtain the solutions numerical models with up 43,000 gridblocks were used. For triggering a viscous fingering effect

Conclusions reached:

Using methods described in a study a complete stabilization of viscous fingering achieved for line-drive and quarter five spot configurations. This is accomplished at the optimum water alternating gas (WAG) ratio when the water and solvent are injected simultaneously.

Comments:

No comparison to experimental results.
Appendix B: Photograph of two Hele-Shaw cells designed for an experimental runs

Fig. B-1 - Photograph of two Hele-Shaw cells designed for experimental runs. (a) Bigger Hele-Shaw cell with 40×40cm internal area. (b) Smaller Hele-Shaw cell with 20×20cm internal area.
Appendix C: Experimental procedure

1. Using 100ml graduated cylinders measure the volume of each fluid to get the right concentration for the mixture. Prepare 200ml of the mixture.
2. Check the density of the mixture using known volume of the fluid and weight; compare it to the calculated value.
3. Measure the temperature of the liquid to correct for the viscosity value.
4. Run the mixture through the pump for 5-10 minutes.
5. Fill in the HS cell with glycerol/water mixture by inclining the HS cell down on the injector side.
6. Place a HS cell horizontally and make sure that it is levelled properly to prevent any gravity effects. Even 1° inclination might compromise the final results.
7. Set up the balances at injection and production points.
8. Run water through the pump for 5-10 minutes to ensure no residual reservoir fluid is left in the tubing.
9. Calibrate the pump to 1ml/min flow rate for water using balances (1g/min).
10. Run the experiment on 1ml/min water injection for 60 minutes, until 1PV is injected. Constantly check on the injection balances that the flowrate is 1ml/min and make adjustments if needed.
11. Keep recording until 2PV injected.
12. Once completed, place HS cell horizontally (outlet at the bottom) and run it with water at high flow rate for 20 minutes to remove remaining mixture.
13. Let the water drip out and run with CO₂ for 2 hours to dry out HS cell.
Appendix D: Calculated relative permeability curves for modelling miscible injection at different mobility ratios

Relative permeability curves calculated using following equations:

\[ k_{rw} = \frac{\mu_w S_w}{\mu(S_w)} \] ................................................................. (3)*

\[ k_{rn} = \frac{\mu_n (1 - S_w)}{\mu(S_w)} \] ................................................................. (4)*

* Lantz (1970)

---

**Fig. D-1:** Combined relative permeability curves for different mobility ratios, M=2, 5, 10, 20, 50 and 100

**Table D-1** - Calculated Relative Permeability for M=2

<table>
<thead>
<tr>
<th>Water Saturation (S_w)</th>
<th>Water Viscosity (cp)</th>
<th>Oil Viscosity</th>
<th>k_w (M=2)</th>
<th>k_n (M=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2.00</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>0.1</td>
<td>1</td>
<td>1.85</td>
<td>0.054</td>
<td>0.972</td>
</tr>
<tr>
<td>0.2</td>
<td>1</td>
<td>1.72</td>
<td>0.116</td>
<td>0.931</td>
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<tr>
<td>0.3</td>
<td>1</td>
<td>1.60</td>
<td>0.188</td>
<td>0.876</td>
</tr>
<tr>
<td>0.4</td>
<td>1</td>
<td>1.48</td>
<td>0.270</td>
<td>0.809</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>1.39</td>
<td>0.360</td>
<td>0.720</td>
</tr>
<tr>
<td>0.6</td>
<td>1</td>
<td>1.30</td>
<td>0.463</td>
<td>0.617</td>
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<tr>
<td>0.7</td>
<td>1</td>
<td>1.21</td>
<td>0.577</td>
<td>0.494</td>
</tr>
<tr>
<td>0.8</td>
<td>1</td>
<td>1.14</td>
<td>0.703</td>
<td>0.351</td>
</tr>
<tr>
<td>0.9</td>
<td>1</td>
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<td>0.842</td>
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<td>1.000</td>
<td>0.000</td>
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**Table D-2** - Calculated Relative Permeability for M=5

<table>
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<th>Water Saturation (S_w)</th>
<th>Water Viscosity (cp)</th>
<th>Oil Viscosity</th>
<th>k_w (M=5)</th>
<th>k_n (M=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>5</td>
<td>0.000</td>
<td>0.400</td>
</tr>
<tr>
<td>0.1</td>
<td>1</td>
<td>3.373</td>
<td>0.030</td>
<td>0.534</td>
</tr>
<tr>
<td>0.2</td>
<td>1</td>
<td>2.869</td>
<td>0.070</td>
<td>0.558</td>
</tr>
<tr>
<td>0.3</td>
<td>1</td>
<td>2.461</td>
<td>0.122</td>
<td>0.569</td>
</tr>
<tr>
<td>0.4</td>
<td>1</td>
<td>2.126</td>
<td>0.188</td>
<td>0.564</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>1.849</td>
<td>0.270</td>
<td>0.541</td>
</tr>
<tr>
<td>0.6</td>
<td>1</td>
<td>1.619</td>
<td>0.371</td>
<td>0.494</td>
</tr>
<tr>
<td>0.7</td>
<td>1</td>
<td>1.426</td>
<td>0.491</td>
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<tr>
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<td>0.801</td>
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</tr>
<tr>
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</tr>
</tbody>
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Table D-3 - Calculated Relative Permeability for $M=10$

<table>
<thead>
<tr>
<th>Water Saturation ($S_w$)</th>
<th>Water Viscosity (cp)</th>
<th>Oil Viscosity</th>
<th>$k_rw$ ($M=10$)</th>
<th>$k_rn$ ($M=10$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>10</td>
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<td>4.156</td>
<td>0.072</td>
<td>0.337</td>
</tr>
<tr>
<td>0.4</td>
<td>1</td>
<td>3.242</td>
<td>0.123</td>
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</tr>
<tr>
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<td>1</td>
<td>2.575</td>
<td>0.194</td>
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</tr>
<tr>
<td>0.6</td>
<td>1</td>
<td>2.078</td>
<td>0.289</td>
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<td>0.7</td>
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<td>1.702</td>
<td>0.411</td>
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<tr>
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<td>1.412</td>
<td>0.567</td>
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</tr>
<tr>
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<td>1.118</td>
<td>0.805</td>
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</tr>
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<td>1</td>
<td>1</td>
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Table D-4 - Calculated Relative Permeability for $M=20$

<table>
<thead>
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<th>Water Saturation ($S_w$)</th>
<th>Water Viscosity (cp)</th>
<th>Oil Viscosity</th>
<th>$k_rw$ ($M=20$)</th>
<th>$k_rn$ ($M=20$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>0.000</td>
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<td>0.3</td>
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<td>0.093</td>
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</tr>
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<td>3.207</td>
<td>0.156</td>
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</tr>
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<td>1.000</td>
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</tr>
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</table>

Table D-5 - Calculated Relative Permeability for $M=50$

<table>
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<th>Water Viscosity (cp)</th>
<th>Oil Viscosity</th>
<th>$k_rw$ ($M=50$)</th>
<th>$k_rn$ ($M=50$)</th>
</tr>
</thead>
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<td>0</td>
<td>1</td>
<td>50</td>
<td>0.000</td>
<td>0.040</td>
</tr>
<tr>
<td>0.1</td>
<td>1</td>
<td>26.380</td>
<td>0.004</td>
<td>0.068</td>
</tr>
<tr>
<td>0.2</td>
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</tr>
<tr>
<td>0.3</td>
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<td>9.323</td>
<td>0.032</td>
<td>0.150</td>
</tr>
<tr>
<td>0.4</td>
<td>1</td>
<td>6.072</td>
<td>0.066</td>
<td>0.198</td>
</tr>
<tr>
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<td>1</td>
<td>4.146</td>
<td>0.121</td>
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<tr>
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<td>1</td>
<td>2.945</td>
<td>0.204</td>
<td>0.272</td>
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<td>2.164</td>
<td>0.324</td>
<td>0.277</td>
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<tr>
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Table D-6 - Calculated Relative Permeability for $M=100$

<table>
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<th>Water Viscosity (cp)</th>
<th>Oil Viscosity</th>
<th>$k_rw$ ($M=100$)</th>
<th>$k_rn$ ($M=100$)</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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<td>0.1</td>
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<td>44.898</td>
<td>0.002</td>
<td>0.040</td>
</tr>
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<td>0.2</td>
<td>1</td>
<td>22.774</td>
<td>0.009</td>
<td>0.070</td>
</tr>
<tr>
<td>0.3</td>
<td>1</td>
<td>12.721</td>
<td>0.024</td>
<td>0.110</td>
</tr>
<tr>
<td>0.4</td>
<td>1</td>
<td>7.675</td>
<td>0.052</td>
<td>0.156</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>4.929</td>
<td>0.101</td>
<td>0.203</td>
</tr>
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<td>3.333</td>
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<td>0.240</td>
</tr>
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<td>1</td>
<td>2.352</td>
<td>0.298</td>
<td>0.255</td>
</tr>
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<td>0.465</td>
<td>0.232</td>
</tr>
<tr>
<td>0.9</td>
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<td>1.298</td>
<td>0.693</td>
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</tr>
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<td>1</td>
<td>1</td>
<td>1.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Appendix E: Comparison of numerical simulation runs with nine-point and five-point pressure difference schemes at M=20 using a diagonal grid

Fig. E-1 - Comparison of numerical simulation runs with nine-point and five-point pressure difference schemes at M=20 using a diagonal grid
Appendix F: Eclipse-100 data file used for simulation of 0.12mm heterogeneity box in the center of the cell at M=20

--- General Model characteristics ---
RUNSPEC

-- Title of the project --
TITLE Hele_Shaw_Cell /

-- Dimensions of the grid NX NY NZ --
DIMENS 400 400 1 /

-- Phases present --
OIL WATER

-- Units --
LAB

-- Well Dimension Data --
WELLDIMS 5 10 5 5 /

-- Start date of the run --
START 2 JUN 2014 00:00:00 /

-- Removing the restriction on monotonically increasing relative permeability curves --
DEBUG 15* -1 /

-- Linear solver stack size --
NSTACK 150 /

-- Selecting nine-point pressure difference scheme --
NINEPOIN /

--- Specifying grid properties ---
GRID

RPTGRID

TRANX ALLNNC /

INIT

NOECHO

-- Grid geometry --
DX 160000*0.1 /
DY 160000*0.1 /
DZ 160000*0.0375 /

TOPS 160000*0 /

-- Porosity --
PORO 160000*1 /

-- Include file with randomly generated permeabilities --
INCLUDE '400x400_Perms.DATA' /
--Defining heterogeneity box and its properties--
BOX
101 300 101 300 1 1 /

PORO
40000*0.68 /

MULTIPLY
-- Array Value ix1 ix2 jy1 jy2 kz1 kz2
PERMX 0.4624 101 300 101 300 1 1 /
PERMY 0.4624 101 300 101 300 1 1 /
PERMZ 0.4624 101 300 101 300 1 1 /
/

EDIT
--PVT & SCAL properties--
PROPS

--Densities of fluids at surface conditions--
DENSITY
-- Oil       water--
0.99       1 /

--PVT Properties of Oil (Dead oil, no gas)--
PVDO
-- P  Bo  ViscO--
1 1 20.00
2 0.999 20.01
3 0.998 20.02
4 0.997 20.03
5 0.996 20.04 /

--Dead oil solution gas--
RSCONST
--Rs Bubble Point Pressure--
0 200 /

--PVT Properties of Water--
PVTW
--Pref Bw  Cw  ViscW--
1 1 0 1 /

--Rock compressibility at reference pressure--
ROCK
-- Pref Cr--
1 5.000E-5 /

--RelPerm for water and oil--
SWOF
-- Sw  Krw  Krow  Pcsw--
0 0 1 0
0.1 0.0078 1.4059 0
0.2 0.0233 1.8647 0
0.3 0.0501 2.3397 0
0.4 0.0927 2.7796 0
0.5 0.1559 3.1178 0
0.6 0.2454 3.2727 0
0.7 0.3675 3.1498 0
0.8 0.5285 2.6424 0
0.9 0.7354 1.6341 0
1 1.0000 0.0000 0
/

--------
REGIONS
--------

----------
--Initialization--
----------

SOLUTION
--Datum depth, Pressure at this depth, OWC, Pc--
EQUIL
0 1 3 0/
--Controls on output from this section--
RPTSOL
'RESTART=1' 'FIP=1' 'PRES' 'SOIL' 'SWAT'

----------------
--Output request--
----------------
SUMMARY

EXCEL
RUNSUM

FPR
FOIP
FOPR
FWPR
FWCT
FOPT
FWPT
FWIR
FWIT

--Wells, completions, rate data--
----------------------------------
SCHEDULE
--Setting simulator control parameters--
TUNING
2* 0.000001 0.0000015 1* 0.02 0.001/
1 0.001 1* 0.001 30 0.1 1* 0.01/
2* 150/

--Number of iterations to update well targets--
NUPCOL
10 /

--Controls on output from schedule section--
RPTSCHED
'RESTART=2' 'SOIL' 'PRES' 'SWAT' 'FIP=1' 'WELLS=1' 'CPU=1' 'NEWTON=1' /

--Specifications of the well--
WELSPECS
--Producer well
'PROD' 'G1' 380 380 0.0375 'OIL' /
--Injector well
'Inj' 'G1' 20 20 0.0375 'WATER' /

--Completion data--
COMPDAT
'PROD' 380 380 1 1 'OPEN' 2* 0.01980 4* /
'Inj' 20 20 1 1 'OPEN' 2* 0.01980 4* /

--Production data--
WCONPROD
'PROD' 'OPEN' 'BHP' 5* 1/

--Injection data--
WCONINJE
'Inj' 'WATER' 'OPEN' 'RESV' 1* 60/

--Timesteps for measurements--
TSTEP
600*0.00166666666/

END
Appendix G: Comparison of numerical simulation results for diagonal and parallel grid with nine point pressure scheme and parallel grid with five point pressure scheme to experimental results at M=20

<table>
<thead>
<tr>
<th>Oil Saturation</th>
<th>0.25PVI</th>
<th>0.50PVI</th>
<th>0.75PVI</th>
<th>1.00PVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation-Diagonal-Nine-Point</td>
<td>Experimental</td>
<td>Simulation-Parallel-Nine-Point</td>
<td>Simulation-Parallel-Five-Point</td>
<td></td>
</tr>
<tr>
<td>Simulation-Diagonal-Nine-Point</td>
<td>Experimental</td>
<td>Simulation-Parallel-Nine-Point</td>
<td>Simulation-Parallel-Five-Point</td>
<td></td>
</tr>
<tr>
<td>Simulation-Diagonal-Nine-Point</td>
<td>Experimental</td>
<td>Simulation-Parallel-Nine-Point</td>
<td>Simulation-Parallel-Five-Point</td>
<td></td>
</tr>
</tbody>
</table>

Fig. G-1 - Comparison of numerical simulation results for diagonal and parallel grid with nine point pressure scheme, and parallel grid with five point pressure scheme to experimental results at M=20
Appendix H: Areal sweep and breakthrough time results together with uncertainties for figures presented in the main body

Table H-1 - Areal sweep results for different mobility ratios in a homogeneous model for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Areal Sweep - Simulation, %</th>
<th>Areal Sweep - Experimental, %</th>
<th>Areal Sweep uncertainty - Simulation, %</th>
<th>Areal Sweep uncertainty - Experimental, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M=2</td>
<td>76.0</td>
<td>60.8</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>M=5</td>
<td>65.6</td>
<td>57.3</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>M=10</td>
<td>57.0</td>
<td>47.1</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>M=20</td>
<td>54.5</td>
<td>41.6</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>M=50</td>
<td>47.9</td>
<td>30.3</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>M=100</td>
<td>41.7</td>
<td>22.7</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
</tbody>
</table>

Table H-2 - Breakthrough time results for different mobility ratios in a homogeneous model for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Breakthrough Time - Simulation, PVI</th>
<th>Breakthrough Time - Experimental, PVI</th>
<th>Breakthrough time uncertainty - Simulation, PVI</th>
<th>Breakthrough time uncertainty - Experimental, PVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>M=2</td>
<td>0.643</td>
<td>0.500</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>M=5</td>
<td>0.493</td>
<td>0.433</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>M=10</td>
<td>0.382</td>
<td>0.350</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>M=20</td>
<td>0.317</td>
<td>0.317</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>M=50</td>
<td>0.258</td>
<td>0.217</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>M=100</td>
<td>0.208</td>
<td>0.183</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
</tbody>
</table>

Table H-3 - Areal sweep results for different heterogeneity thicknesses at M=20 for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Areal Sweep - Simulation, %</th>
<th>Areal Sweep - Experimental, %</th>
<th>Areal Sweep uncertainty - Simulation, %</th>
<th>Areal Sweep uncertainty - Experimental, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05mm</td>
<td>59.3</td>
<td>51.6</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.12mm</td>
<td>64.2</td>
<td>50.7</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.20mm</td>
<td>54.3</td>
<td>50.9</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>54.5</td>
<td>41.6</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
</tbody>
</table>

Table H-4 - Breakthrough time results for different heterogeneity thicknesses at M=20 for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Breakthrough Time - Simulation, PVI</th>
<th>Breakthrough Time - Experimental, PVI</th>
<th>Breakthrough time uncertainty - Simulation, PVI</th>
<th>Breakthrough time uncertainty - Experimental, PVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05mm</td>
<td>0.335</td>
<td>0.433</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.12mm</td>
<td>0.368</td>
<td>0.417</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.20mm</td>
<td>0.353</td>
<td>0.350</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>0.317</td>
<td>0.317</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
</tbody>
</table>
### Table H-5 - Areal sweep results for different heterogeneity locations at M=20 for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Areal Sweep - Simulation, %</th>
<th>Areal Sweep - Experimental, %</th>
<th>Areal Sweep uncertainty - Simulation, %</th>
<th>Areal Sweep uncertainty - Experimental, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12mm Injector</td>
<td>63.1</td>
<td>57.2</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.12mm Center</td>
<td>64.2</td>
<td>50.7</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.12mm Producer</td>
<td>63.0</td>
<td>50.5</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.12mm Side</td>
<td>57.7</td>
<td>55.8</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>54.5</td>
<td>41.6</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
</tbody>
</table>

### Table H-6 - Breakthrough time results for different heterogeneity locations at M=20 for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Breakthrough Time - Simulation, PVI</th>
<th>Breakthrough Time - Experimental, PVI</th>
<th>Breakthrough time uncertainty - Simulation, PVI</th>
<th>Breakthrough time uncertainty - Experimental, PVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12mm Injector</td>
<td>0.348</td>
<td>0.333</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.12mm Center</td>
<td>0.368</td>
<td>0.417</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.12mm Producer</td>
<td>0.352</td>
<td>0.367</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.12mm Side</td>
<td>0.313</td>
<td>0.367</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>0.317</td>
<td>0.317</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
</tbody>
</table>

### Table H-7 - Areal sweep results for different heterogeneity orientations at M=20 for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Areal Sweep - Simulation, %</th>
<th>Areal Sweep - Experimental, %</th>
<th>Areal Sweep uncertainty - Simulation, %</th>
<th>Areal Sweep uncertainty - Experimental, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12mm</td>
<td>64.2</td>
<td>50.7</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.12mm Rotated</td>
<td>67.5</td>
<td>56.6</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.20mm</td>
<td>54.3</td>
<td>50.9</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>0.20mm Rotated</td>
<td>54.5</td>
<td>50.9</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>54.5</td>
<td>41.6</td>
<td>+1.3/-5.1</td>
<td>+/- 2.0</td>
</tr>
</tbody>
</table>

### Table H-8 - Breakthrough time results for different heterogeneity orientations at M=20 for numerical simulations and experimental runs together with uncertainties

<table>
<thead>
<tr>
<th>#Run</th>
<th>Breakthrough Time - Simulation, PVI</th>
<th>Breakthrough Time - Experimental, PVI</th>
<th>Breakthrough time uncertainty - Simulation, PVI</th>
<th>Breakthrough time uncertainty - Experimental, PVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12mm</td>
<td>0.368</td>
<td>0.417</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.12mm Rotated</td>
<td>0.393</td>
<td>0.317</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.20mm</td>
<td>0.353</td>
<td>0.350</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>0.20mm Rotated</td>
<td>0.315</td>
<td>0.350</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>0.317</td>
<td>0.317</td>
<td>+/-0.019</td>
<td>+/-0.015</td>
</tr>
</tbody>
</table>