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SIMULATION STUDY OF THE IMPACT OF MOBILITY RATIO ON MULTILAYERED RESERVOIR DURING WATERFLOODING PROCESS

By

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(10597)

FINAL PROJECT II

DISSERTATION

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Submitted to the Petroleum Engineering Program in Partial Fulfillment of the Requirements for the Bachelor of Engineering (Hons) Degree in Petroleum Engineering on 12th August 2011

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CERTIFICATE OF APPROVAL

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BACHELOR OF ENGINEERING (Hons)
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TRONOH, PERAK
August 2011

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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10597

ABSTRACT

Implementation of waterflooding technique in Waha reservoir requires the injection of water into the oil zone for oil displacement, due to the primary recovery mechanism used in the Waha reservoir. Previous study done concludes that there are two factors that highly affected the waterflooding performances, which are the mobility ratio and reservoir heterogeneity. Therefore, a numerical approach was used to study the effect of mobility ratio and reservoir heterogeneity in the waterflooding project with quarter of Five-Spot Injection Pattern. Eclipse simulator was used, in which the results was estimated using the combination of Buckley-Leverett and Dykstra-Parson method. Some theories involved were also discussed in this paper, such as Frontal Advance Equation, Fractional Flow Equation and relevant researches done by others. Generally, the mobility ratio more than 1 (M>1) will achieve early breakthrough with less oil recovery, while mobility ratio less than 1 (M<1) will achieve late breakthrough with more oil recovery. Meanwhile, permeability is highly affecting waterflooding performances in reservoir heterogeneity factor, compared to porosity and thickness. High permeability formation enables the fluid to travel faster, and increase the mobility ratio of the displacement, while low permeability formation enables the fluid to travel slower, and decrease the mobility ratio of the displacement. The estimation based on simulated results indicate that the mobility ratio equal to 0.8 (M=0.8) will optimize the waterflooding performances, given the permeability variation of 0.4

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ABBREVIATIONS AND NOMENCLATURES

OOIP	Original Oil in Place
BBOE	Billion Barrels of Oil Equivalent
EOR	Enhanced Oil Recovery
RF	Overall Recovery Factor
M	Mobility Ratio
λ	Mobility of Fluid
K_{rw}	Relative Permeability of Water
K_{ro}	Relative Permeability of Oil
μ_w	Viscosity of Water
μ_o	Viscosity of Oil
FOPT	Total Field Oil Production
FOE	Field Oil Recovery Factor
FWCT	Field Oil Water Cut

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND STUDY

In oil and gas industry, the oil is produced from a reservoir through three different stages, namely, primary recovery, secondary recovery and tertiary recovery.

According to Ahmad (2006),

> "Primary recovery describes the production of hydrocarbons under the natural drive mechanism present in the reservoir. Secondary oil recovery refers to the additional recovery that results from the conventional methods of water injection and gas injection. Tertiary (enhanced) oil recovery is additional recovery over and above what could be recovered by primary and secondary methods." [1]

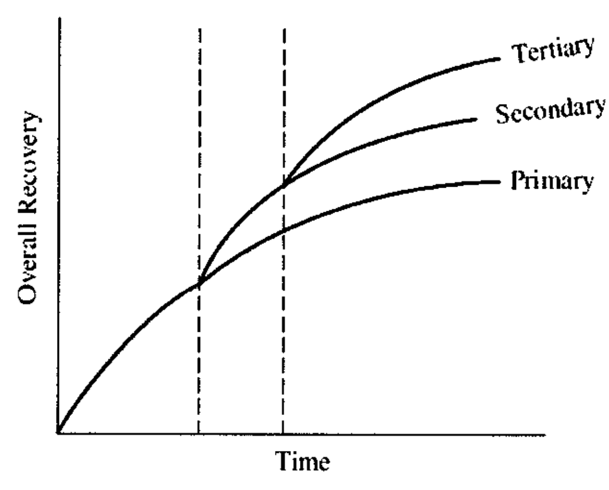


Figure 1: Graph Overall Recovery

Based on description of Ahmad (2006), the secondary recovery consists of two different methods to improve the recovery, which are water injection and gas injection. [1] Gulick and McCain (1998) indicates that, "One of the cheapest and most popular methods of restoring and maintaining reservoir energy is to inject water into the reservoir; i.e., waterflooding." [2]

According to Craig (1971),

> "Its popularity is accounted for by the general availability of water, the relative ease with which water is injected, owing to the hydraulic head it possesses in the injection well, the ability with which water spreads through an oil-bearing formation and water's efficiency in displacing oil." [3]

Craig also mentioned that the first waterflood occurred in the Pithole City area of Pennsylvania in 1865, but, it was not until the early 1950's that the general applicability of waterflooding was recognized. [3] This indicates that the waterflooding technique is developed for about 50 years, makes this technique mature and reliable. Sandrea (2007) summarized that the recovery rates that can be achieved with waterflooding technique is in the range of 25 – 30% of original oil in place (OOIP), even though it is theoretically possible for recovery up to 50% of OOIP. [4]

According to Willhite (1986), waterflooding is a technique in which water is injected for two purposes, either pressure maintenance or oil displacement. [5] In pressure maintenance, the water is injected into the aquifer to maintain the pressure for water drive mechanism. Meanwhile, the oil displacement purpose requires the injection of water into the oil zone in the reservoir, in order to sweep or displace the remaining oil in the reservoir.

1.2 WAHA RESERVOIR OVERVIEW

According to Klett (1997), the Sirte Basin provinces that located in Libya ranks 15th among the world's petroleum provinces, with 43.1 billion barrels of oil equivalent (BBOE) of known petroleum volume. [6] The JB Libyan field (JB Field) is located in southeastern concession 20 in the Sirte Basin. There are three formations exist in the JB Field, from the top: Zmam, Waha and Gargaf.

Figure 2: Location of Sirte Basin

The main formation, Waha that consist the major part of hydrocarbons is currently produced under the natural depletion. Field observation indicates that the Waha formation is a saturated reservoir, enabling the primary recovery by solution-gas drive mechanism with weak aquifer (water-drive) support. In the Waha reservoir, there are 30 potential wells, which can be grouped according 8 wells with very long term shut in since 1988, 11 wells with shorter term shut in since 1998 and 11 wells still on production.

1.3 CONSIDERATION OF WATERFLOODING PROJECT

Thomas (1989) pointed out that primary reservoir driving mechanisms must be considered in determining the suitability of a candidate reservoir for waterflooding. [7] Based on the production history of Waha reservoir, there are two drive mechanisms present during the primary recovery, which are the solution-gas drive and water drive.

The solution-gas drive mechanism present in the Waha formation is the main driving mechanism used in primary recovery. This drive mechanism use the energy derived from the gas dissolved in the fluid. As the reservoir fluids enter the wellbore, the changes in pressure cause the gas to break from solution to create a commingled flow of gas and liquid that aids the production.

According to Thomas (1989), the solution-gas drive mechanism is generally considered as the best candidates for the implementation of waterflooding technique. This is due to the low oil recovery by the primary recovery enables a great potential for additional recovery by the waterflooding, with the possibility of creating artificial water-drive mechanism that doubles the oil recovery. [7]

The water-drive mechanism present in the Waha formation is categorized as the weak water-drive mechanism. This type of drive mechanism requires the existence of an aquifer. The energy is derived from the water moving into the oil zone from the aquifer below, displacing the oil until the aquifer energy is expanded or the well eventually produces too much water to be viable.

Thomas (1989) also describe that the consideration of water-drive mechanism for waterflooding is depending on the strength of the drive mechanism itself. In strong water-drive reservoirs, the waterflooding technique for oil displacement is rarely considered due to the natural ongoing water influx. [7]

1.4 PROBLEM STATEMENT

Gulick (1998) describe that the low oil recovery achieved by the primary recovery is mainly due to the fact that the natural drive mechanism has low reservoir energy, in addition of the heterogeneity of the reservoir and the mobility ratio during the displacement process. [2] In this stage, the production is no longer economical and secondary recovery should be implemented to improve the oil recovery.

Sandrea (2007) mentions that "Solution gas drive is the most widespread natural drive mechanism in the majority of the world's reservoirs and can provide a recovery of up to 20% of OOIP." He also mentions that "Roughly one-third of the world's reservoirs have natural water drives." [4] As the most of the world's oil productions is using the solution gas drive and water drive mechanism, waterflooding technique is considered to improve the oil recovery.

1.5 OBJECTIVES

1. To investigate the performance of waterflooding with Five-Spot Pattern.

2. To study the effect of the mobility ratio towards the waterflooding performances.

3. To study the effect of reservoir heterogeneity on waterflooding performances.

1.6 SCOPE OF STUDY

1. Understanding of Waha reservoir properties.
2. Designing and modeling of waterflooding project in Eclipse simulator.
3. Determination of the variables for different mobility ratio.
4. Determination of the variables for different reservoir heterogeneity.
5. Analysis of the waterflooding performances using the Eclipse simulator.

1.7 RELEVANCY AND FEASIBILITY OF THE PROJECT

This numerical study result in optimization of the waterflooding performances, given that the mobility ratio and reservoir heterogeneity as the variables. This study enable the implementation of waterflooding technique as secondary recovery to improve the oil recovery is optimum.

This study is also feasible, as it uses a numerical approach, in which Eclipse simulator was used to model the implementation of waterflooding technique in Waha reservoir. The Eclipse simulator uses the combination of Buckley-Leverett and Dykstra-Parson method to approximate the results in this study.

CHAPTER 2: LITERATURE REVIEW

2.1 WATERFLOODING TECHNIQUE

Waterflooding is a secondary recovery method to improve the oil recovery. According to Willhite (1986), it is a technique of injecting water into a reservoir to serve two purposes, either pressure maintenance or oil displacement. In pressure maintenance purpose, the water is injected into the aquifer to maintain the pressure for the water drive mechanism, when the oil displacement purpose requires the injection of water into oil zone in the reservoir, in order to sweep or displace the remaining oil in the reservoir. [5]

According to Ahmad (2006), the implementation of waterflooding technique for pressure maintenance purpose can only be done to water-drive reservoirs that are classified as strong-water-drive. The implementation is used in supporting the water drive mechanism to achieve higher production rate and balance the spaces and influx volumes. [1]

Ahmad (2006) adds that the implementation of waterflooding technique for oil displacement purpose can be done to reservoirs that depend on solution gas drive mechanism only or having a weak-water-drive. The water injected into the oil zone is able to displace the oil from the pores to the producer in piston like manner, under ideal conditions. [1]

Ahmad (2006) also mentions that the performances of waterflooding are related to the Overall Recovery Factor (RF). Higher overall recovery efficiency will result in higher percentage of oil recovery. The major factors that affect the RF are: [1]

- Fluid Mobility
- Reservoir Heterogeneity

2.2 FIVE SPOT INJECTION PATTERN

One of the steps in designing a waterflooding project is flood pattern selection. The objective is to select the proper pattern that will provide the injection fluid with the maximum possible contact with the crude oil. This can be achieved by converting the existing production well into injectors and drilling infill injection wells.

It is agreed that the pattern geometry plays a major role in determining the oil recovery, during secondary and enhanced oil recovery operations. [9] In regular injection patterns, there are several basic well patterns that are commonly used in waterflooding, such as the Four Spot, Five Spot, Seven Spot, Nine Spot, Direct Line Drive and Staggered Line Drive.

In this study, the pattern used for the waterflooding project is the Five Spot Pattern. Previous study concluded that the five-spot pattern has better sweep efficiency than a common staggered-line-drive for very favorable mobility ratio. [9] This pattern is having four injection wells surrounding one production wells, thus form a square with a production well at the center.

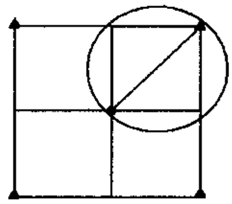


Figure 3: Five-Spot Pattern

The Five-Spot Pattern is a special pattern, in which it is a staggered line drive with the distance between all like wells is constant. However, in any study or research involving the usage of the Five-Spot Pattern, only a quarter of the Five-Spot Pattern is focused. This is due to the assumption that the oil displacement of the waterflooding process is identical to each other due to the distance from injector to producer is constant.

2.3 BUCKLEY-LEVERETT DISPLACEMENT THEORY

The mechanism of the waterflooding technique in oil displacement is best described by the Buckley-Leverett Displacement Theory. Buckley and Leverett (1942) developed a well-established theory, named the 'Frontal Displacement Theory'. [8] This classic theory consists of two equations:

- Frontal Advance Equation

  The Frontal Advance Equation was developed from the Principle of Mass Conservation, commonly known as the Continuity Equation. The equation was developed by the Buckley and Leverett to describe the relationship of oil displaced by water in a linear system.

$$\left(\frac{dx}{dt}\right)_{S_w} = \frac{q_t}{\phi A}\left(\frac{df_w}{dS_w}\right)_t$$

Figure 4: Frontal Advance Equation

- Fractional Flow Equation

  The Fractional Flow Equation was developed from the combination of the Frontal Advance Equation and Darcy's Law. This equation can be used in order to determine the breakthrough time based on fractional flow (water cut) curves.

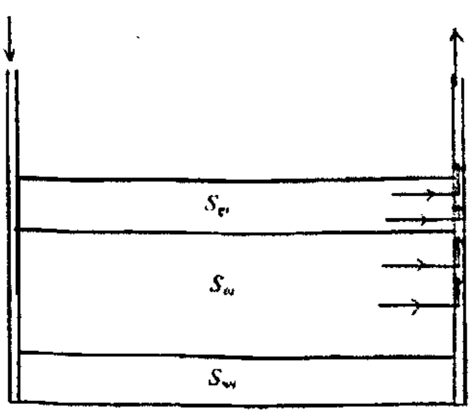
$$f_w = \frac{1+\left(\frac{0.001127k_o A}{\mu_o q_t}\right)\left[\frac{\partial P_c}{\partial x} - g\Delta\rho\sin\alpha\right]}{1+\frac{k_o}{k_w}\frac{\mu_w}{\mu_o}}$$

Figure 5: Fractional Flow Equation

2.4 FLUID SATURATION DISTRIBUTION

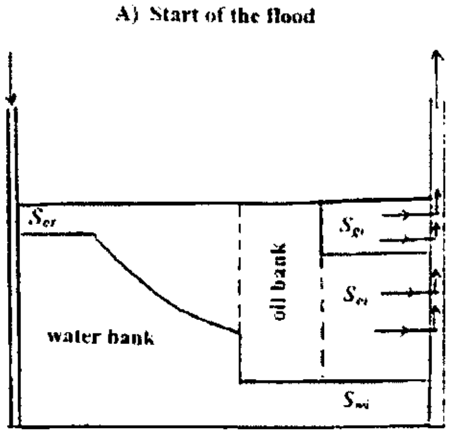
Based on the Frontal Advance Equation and Fractional Flow Equation, the Buckley and Leverett (1942) plot the water saturation, S_w against the distance, x. This plot is more known as the water saturation profile can be used to describe the water displacement during the waterflooding.

However, Ahmad (2006) stated that when a solution gas-drive reservoir is under consideration for waterflooding, substantial gas saturation usually exists in the reservoir at the start of the flood. [1] Therefore, the saturation profile is differs than the original theory produced by Buckley and Leverett.



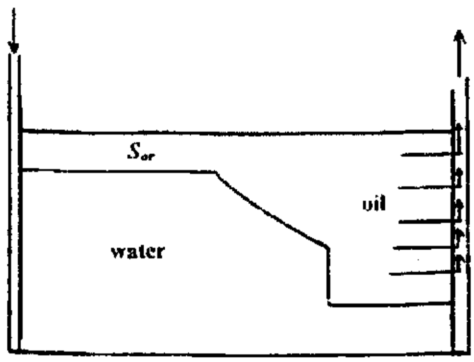
A) Start of the flood

In the initial condition before the waterflooding starts, the saturation profile can be described in three layers, where it were filled with initial saturation of gas, oil and water.



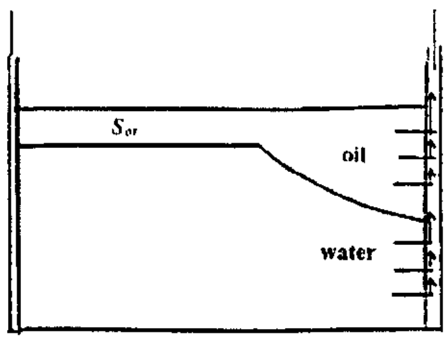
B) interference

The water injected will displace the pore space occupied by the free gas during the displacement. The increase in oil saturation during the displacement is exactly equal to the decrease in the initial gas saturation, also referred as 'oil resaturation effect'.



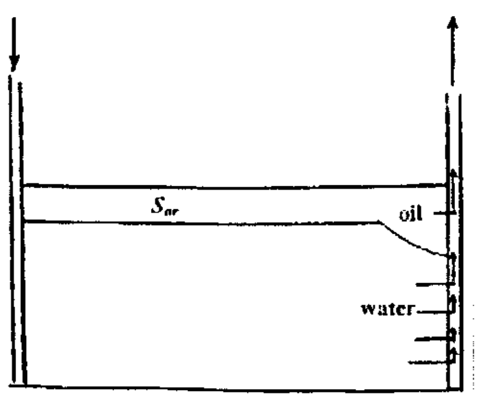
C) Fill-up

Due to continuation of water injection, the leading edge of the oil bank reaches the producing well, which can be referred as 'fill-up stage'.



D) water breakthrough

Then, the water will displace the oil bank towards the producer. The moment where the water reaches the producer is known as 'breakthrough'.



E) near end of the project

Lastly, the water will displace all the oil except the residual oil in the formation, indicating that the water displacement ends.

Figure 6: Saturation Profile for cases where initial gas saturation exist

2.5 BREAKTHROUGH TIME DETERMINATION

The performance of the waterflooding can be seen through its breakthrough time. Breakthrough time is the time, where the water injected arrives at the production wells, in which the oil can be assumed to be fully displaced. In the Buckley-Leverett method, the breakthrough time can be found by plotting the fractional flow, f_w versus S_w graph.

Based on the fractional flow equation, we can see that the capillary forces and gravitational forces can affect the fractional flow equation. Capillary forces tend to oppose the formation of the saturation discontinuities in homogenous sand, while the gravitational forces tend to promote the complete vertical segregation of oil and water.

It is agreed that during the oil production, the level of the zero capillary pressure rises, creating the tendency for the water saturation throughout the reservoir to increase in order to achieve the equilibrium. The effect of the capillary terms can be further seen in the graph of water cut versus the water saturation, as per below:

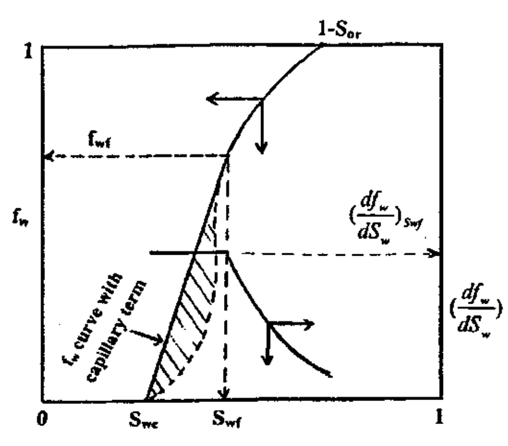


Figure 7: Fractional Flow Curves with Capillary Term

Therefore, the breakthrough time can be determined at point in which the time where the value of fractional flow stops increase rapidly. In the cases, where the capillary term is neglected, breakthrough time can be determined by the point where the tangent of the curves.

2.6 MOBILITY RATIO

The fluid mobility will determine the mobility ratio, which plays an important role in affecting the performances of a waterflooding. Different mobility ratio will results in different breakthrough time and oil recovery. Mobility ratio, M can be defined as the mobility of the displacing fluid to the mobility of the displaced fluid. Mobility of any fluid, λ is defined as the ratio of the effective permeability of the fluid to the fluid viscosity. Since, it is agreed that the effective permeability can be calculated by multiplying the relative permeability with absolute permeability; the mobility ratio can be calculated. [1]

$$M = \frac{k_{rw} / \mu_w}{k_{ro} / \mu_o}$$

Where, M = Mobility Ratio

K_{rw} = Relative Permeability of Water

K_{ro} = Relative Permeability of Oil

μ_w = Viscosity of Water

μ_o = Viscosity of Oil

Figure 8: Mobility Ratio Equation

Previous study done by Wang (1998) summarizes that, when the mobility ratio is less or equal to 1, the displacement of oil will result in piston-like movement. [8] Assuming that the properties of the fluid effective permeability does not changes, mobility ratio less than 1 indicating that the water is more viscous compared to the oil viscosity.

Figure 9: Illustration on Piston-like Displacement

Guliyev (2008) supports Wang (1998) by stating that as the viscosity of the water is higher compared to the viscosity of oil, the velocity of the water during the displacement is relatively lower compared to the oil. This will result the oil to be remain in front of the water during the displacement. The displacement will be steadier, as no water with higher velocity can bypass the oil. Mobility ratio less than 1 is favorable in waterflooding process, as it can recover more oil at the breakthrough. [10]

Ahmad (2006) defines the breakthrough as case or condition where the water injected arrives at the production wells. [1] Wang (1998) also summarizes that when the mobility ratio is higher than 1, the displacement of oil will results in fingering-like movement. [8] Assuming that the properties of the fluid effective permeability remains constant, mobility ratio more than 1 indicating that the oil is more viscous compared to the water viscosity.

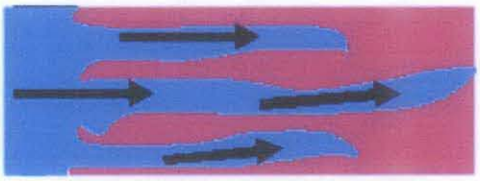


Figure 10: Fingering Displacement

Guliyev (2008) supports Wang (1998) by stating that as the viscosity of the oil is higher compared to the viscosity of water, the velocity of the oil during the displacement is relatively lower compared to the water. This will result the water tends to bypass the oil during the displacement. The displacement will be more unsteady, as more water with higher velocity can bypass the oil. Mobility ratio more than 1 is not favored in waterflooding process, as it recovers less oil at the breakthrough. [10]

Craig et al. (1955) performed experimental studies on the influence of the fluid mobility on the areal sweep efficiency resulting from water or gas injection. Areal sweep efficiency is simply the ratio of area swept by water over the total area. In his study, the areal sweep efficiency was determined from x-ray shadowgraphs taken during various stages of the displacement as illustrated below. [11]

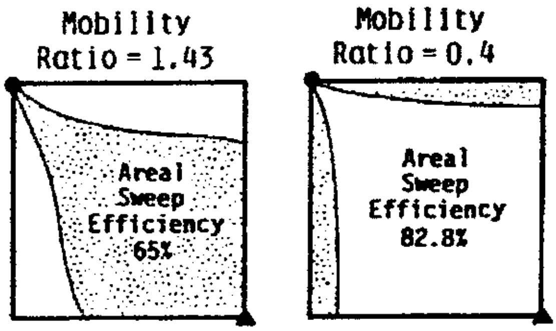


Figure 11: Areal Sweep Efficiency at Breakthrough

Ahmad (2006) defines the areal sweep efficiency is as the area swept by water divided by the total area. [1] As we can see, the result of Craig study clearly indicates that low mobility ratio has better areal sweep efficiency compared to the high mobility ratio at the breakthrough. Higher areal sweep efficiency can be used to indicate the volume of the oil displaced out from the reservoir, in which it is assumed to be fully produced. [11]

2.7 RESERVOIR HETEROGENEITY

Thomas et al. (1989) pointed out that lithology has a profound influence on the efficiency of waterflooding in a particular reservoir. Reservoir lithology and rock properties that affect flood ability and success are: [7]

- Porosity
- Permeability
- Net thickness

Previous study by El-Khatib (2001) describes that the petrophysical properties of oil-bearing formations are normally heterogeneous. The most significant properties that affect waterflooding performance are the absolute permeability and its variation normal to the direction of flow. This variation causes the displacing fluid to advance faster in zones of higher permeability and thus results in earlier breakthrough in such layers.

Dykstra and Parsons (1950) introduced the concept of permeability variation, V which is designed to describe the degree of heterogeneity within the reservoir. [14] In the method, the permeability was plotted against the percentage of the thickness in a log-probability graph, and permeability variation, V was estimated by the formula.

$$V = \frac{k_{50} - k_{84.1}}{k_{50}}$$

Figure 12: Permeability Variation Formula

CHAPTER 3: METHODOLOGY AND PROJECT WORK

3.1 GENERAL PROJECT WORKFLOW

The general project workflow is the guideline and procedures used to produce the results required in this study. The usage of this workflow will ensure that work is conducted in acceptable and organized conditions to achieve the objectives of this study.

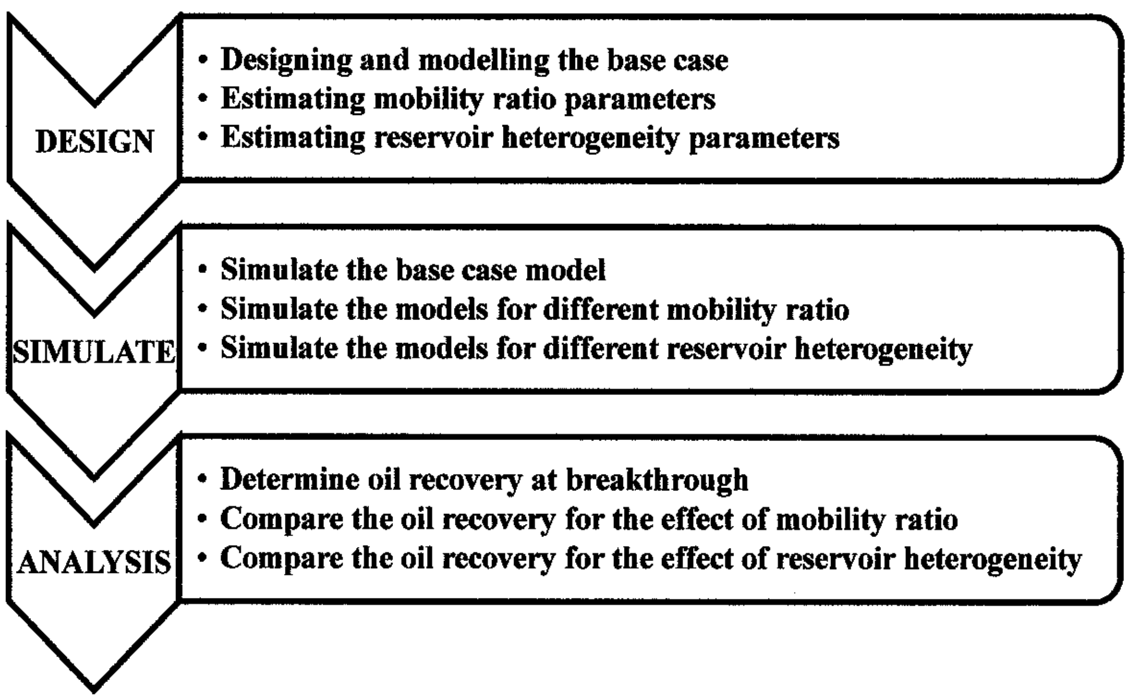


Figure 13: General Project Workflow

3.2 DESIGNING AND MODELLING THE BASE CASE

As the area of the Five-Spot Pattern focused on this study is given as 435,600 ft^2, the base case model was designed as 660 ft X 660 ft, with 10 X 10 blocks for the geometry type of block-centered geometry.

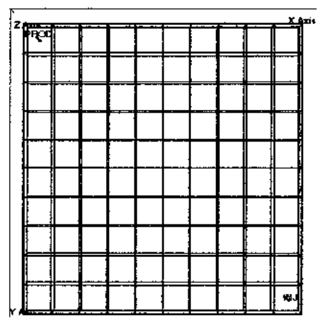


Figure 14: Top View of the Model

In term of the thickness, the base case model is designed with three layers with different thickness, as given in the Waha reservoir properties. The formation thickness is 79 ft, with three distinctive layers with thickness from the top: 14 ft, 52ft, and 13ft.

Figure 15: Front View of the Model

In this base case model, the injection well was located in the grid (1, 1) while the production well was located in the grid (10, 10). Both the injection and production wells are perforating all the three layers.

Figure 16: Side View of the Model

The others parameters used in designing the base case model are referred to the given Waha reservoir properties, which can be referred in the appendices section. The model for Eclipse simulator was build using the 'Notepad'.

```
RUNSPEC

TITLE
WAHA

DIMENS
10 10 3 /

OIL
WATER
GAS
DISGAS

FIELD

TABDIMS
1 1 20 20 1 20 /

WELLDIMS
2 3 2 1 /

UNIFOUT

START
1 JAN 2008 /

GRID

DX
300*66 /

DY
300*66 /

DZ
100*14 100*52 100*13 /

BOX
1 10 1 10 1 1 /

TOPS
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ENDBOX

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PERMY
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PERMZ
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INIT

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ROCK
2489 3E-6 /

DENSITY
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SOLUTION

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RSVD
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7160 1.00040 /

RPTRST
BASIC=2 NORST=1 /

SUMMARY


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'PROD' 1 1 2 /
'PROD' 1 1 3 /
/

COPT
'PROD' 1 1 1 /
'PROD' 1 1 2 /
'PROD' 1 1 3 /
/


FPR

FOE

WBHP
/

FWCT
FOPR
FWPR
FOPT
FWPT
```

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WOPR
/

WWCT
PROD/

TCPU

EXCEL

SCHEDULE

RPTRST
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INJ  G2 10 10 7100 WATER /
/

COMPDAT
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INJ  10 10 1 3 OPEN 2* 0.667 /
/

WCONPROD
PROD OPEN LRATE 3* 2270 1* 1000 /
/

WCONINJ
INJ WATER OPEN RATE 2500 3* 4000 /
/

WECON
PROD 2* 0.9 2* CON Y /
/

TSTEP
10*100 /

END
```

Figure 17: Base Case Model in Notepad

3.3 ESTIMATION OF MOBILITY RATIO

In order to calculate the mobility ratio, relative permeability was plotted against the water saturation. From the plot, we can determine that the k_{ro} and k_{rw} parameters, results as k_{rw}=0.63 at S_{or} and k_{ro}=0.98 at S_{wi}.

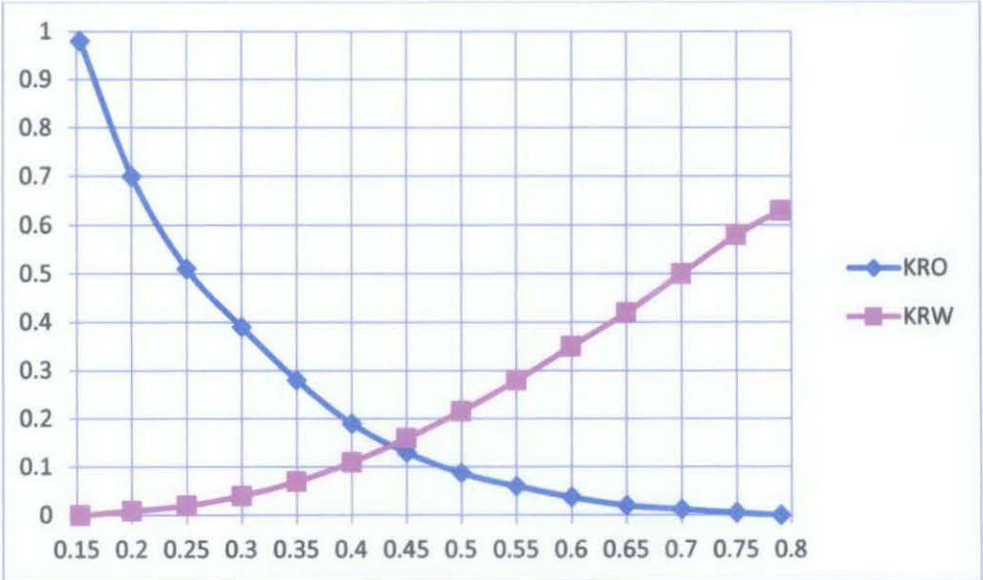

Figure 18: Relative Permeability versus Water Saturation

Using the formula, we can calculate mobility ratio of our base case model and predicted the water viscosity for our study, assuming the oil viscosity and relative permeability are constant.

$$M = \frac{k_{rw}}{k_{ro}} \frac{\mu_o}{\mu_w} = \frac{0.63}{0.98}\left(\frac{0.423}{0.27}\right) = 1$$

Figure 19: Example Calculation of Mobility Ratio

Case	Mobility Ratio	Water Viscosity
1	0.5	0.54
2	1	0.27
3	2	0.14

Figure 20: Water Viscosity for different Mobility Ratio

3.4 ESTIMATION OF RESERVOIR HETEROGENEITY

In order to calculate the reservoir heterogeneity variance, the permeability was plotted against percentage of formation thickness in a log-probability chart. From the plot, we can determine that the $k_{84.1}$ and k_{50} parameters, results as $k_{84.1}=95$ and $k_{50}=150$.

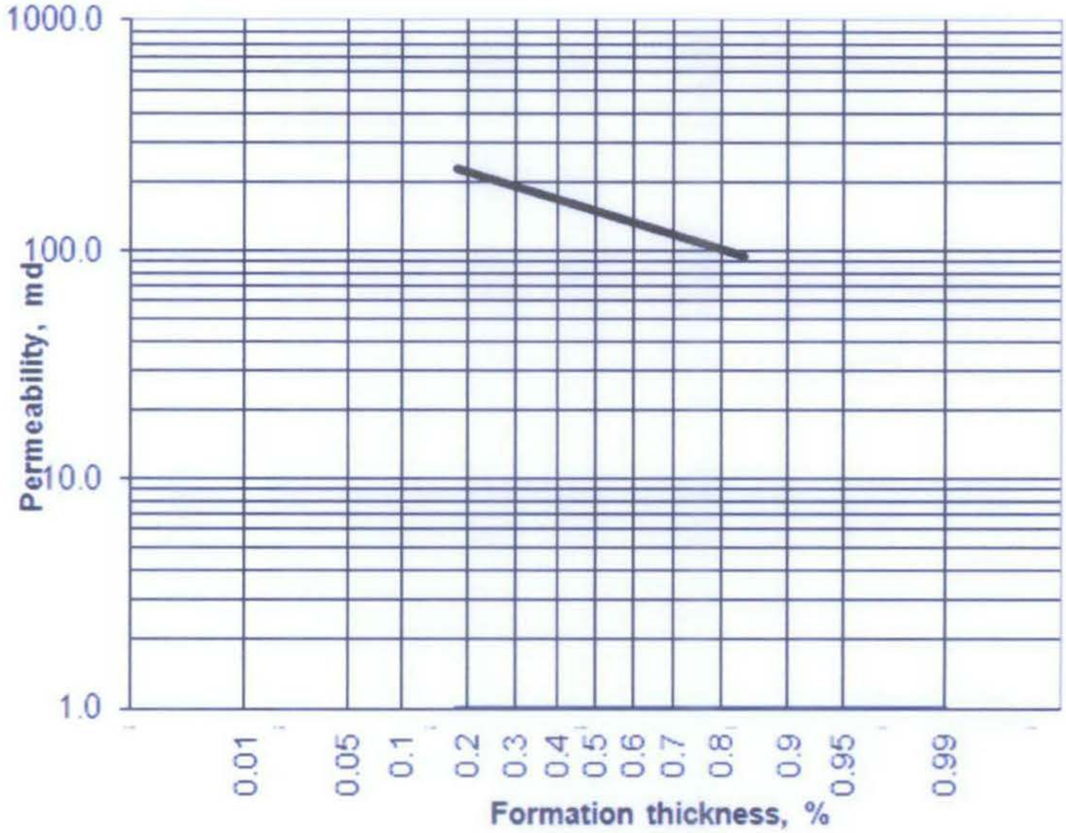

Figure 21: Log-Probability Chart

From this chart, we can calculate that the permeability variance using the Dykstra-Parson formula, results as 0.4.

$$V = \frac{k_{50} - k_{84.1}}{k_{50}} = \frac{150 - 95}{150} = 0.4$$

Figure 22: Example calculation of Permeability Variance

3.5 KEY MILESTONE

In order to complete the project, student plays an important and crucial role as the researcher, in which full commitment, initiative and efforts are required to complete the tasks. Therefore, supervision and assistance from supervisor is necessary to ensure that the student is on the correct track and timeline. This could only be achieved by a good and consistence communication between the student and the supervisor, in which weekly meeting can be used as the best platform for the communication.

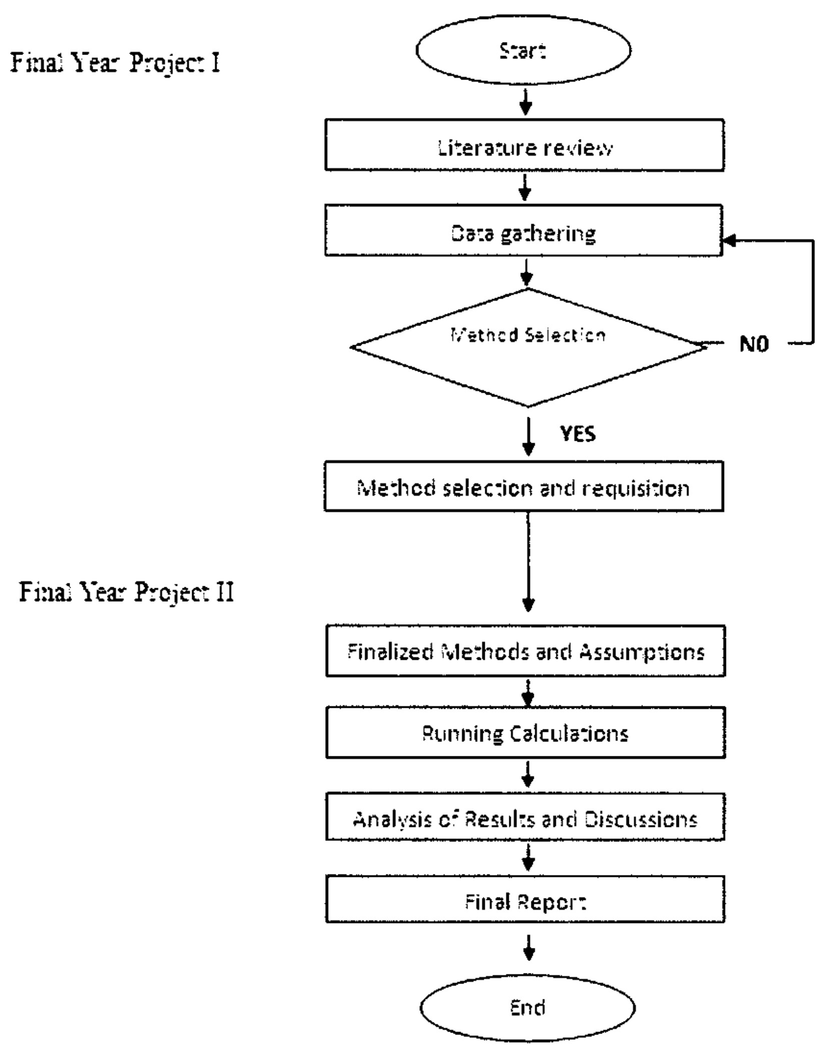

Figure 23: Key Milestone

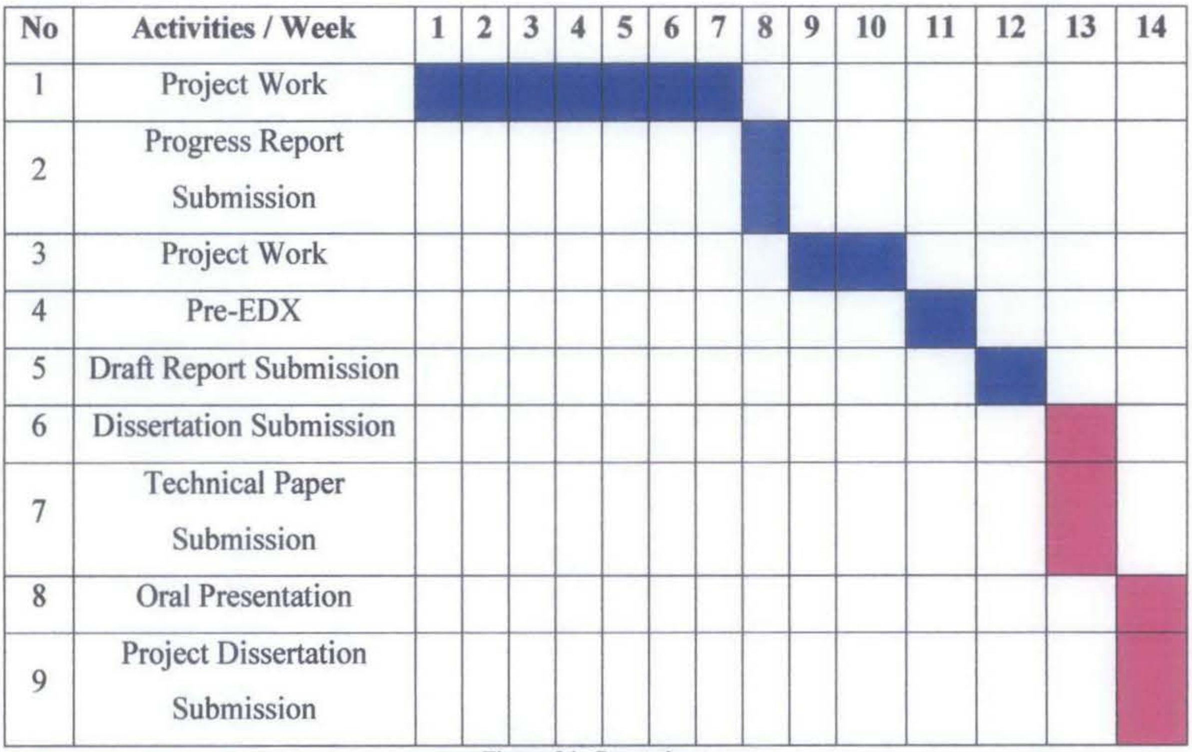

Figure 24: Gantt chart

CHAPTER 4: RESULT AND DISCUSSION

4.1 WATERFLOODING PERFORMANCE IN FIVE-SPOT PATTERN

The performances of the waterflooding technique in Waha formation can be seen by plotting the FWCT versus Time curves and FOE versus Time. From the FWCT versus Time curves, we can determine the breakthrough time for the base case model of the waterflooding project. Breakthrough time is the time required for the waterflooding front to arrive at the producer well.

This can be done by drawing a straight line from the initial point to the tangent of the water cut curves. The initial point can be defined as the point where the water cut is starting to increase from 0. The time required to achieve the tangent of the water cut curve is known as the breakthrough time. The time for the field to achieve the breakthrough is estimated at days 155.

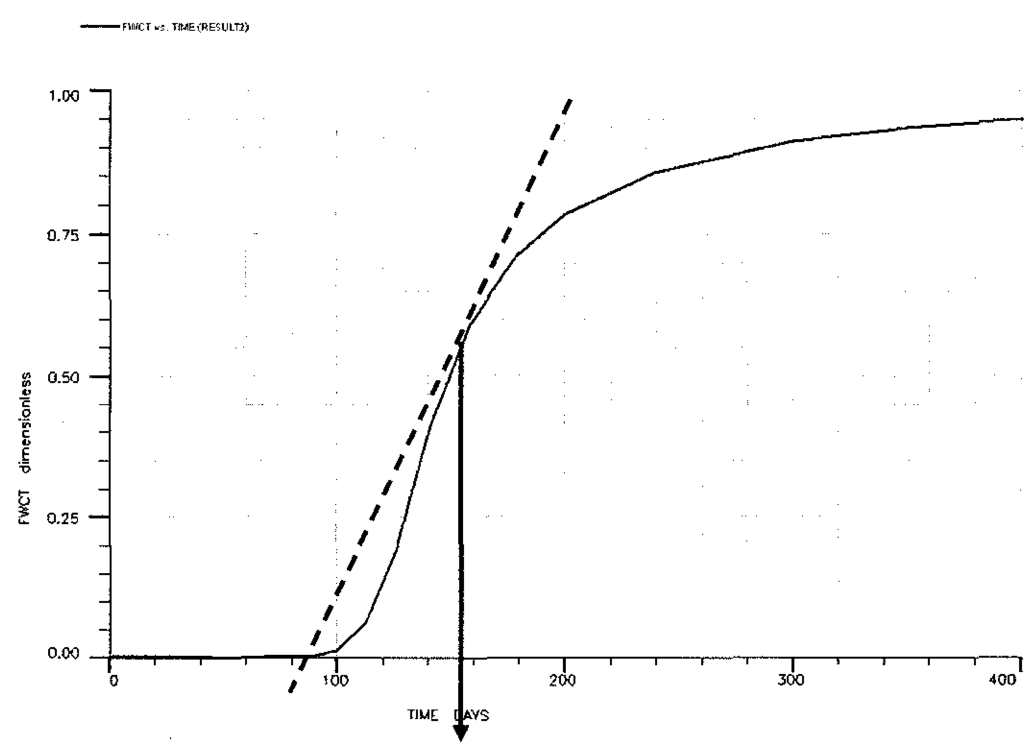

Figure 25: FWCT versus Time (Base Case for Field)

Next, the FOE versus Time curves was plotted to determine the value of oil recovery that can be achieved by the base case model. Based on the breakthrough time, we draw a straight line to determine the oil recovery that can be achieved. The oil recovery achieved by the base case model at breakthrough is identified as 0.53.

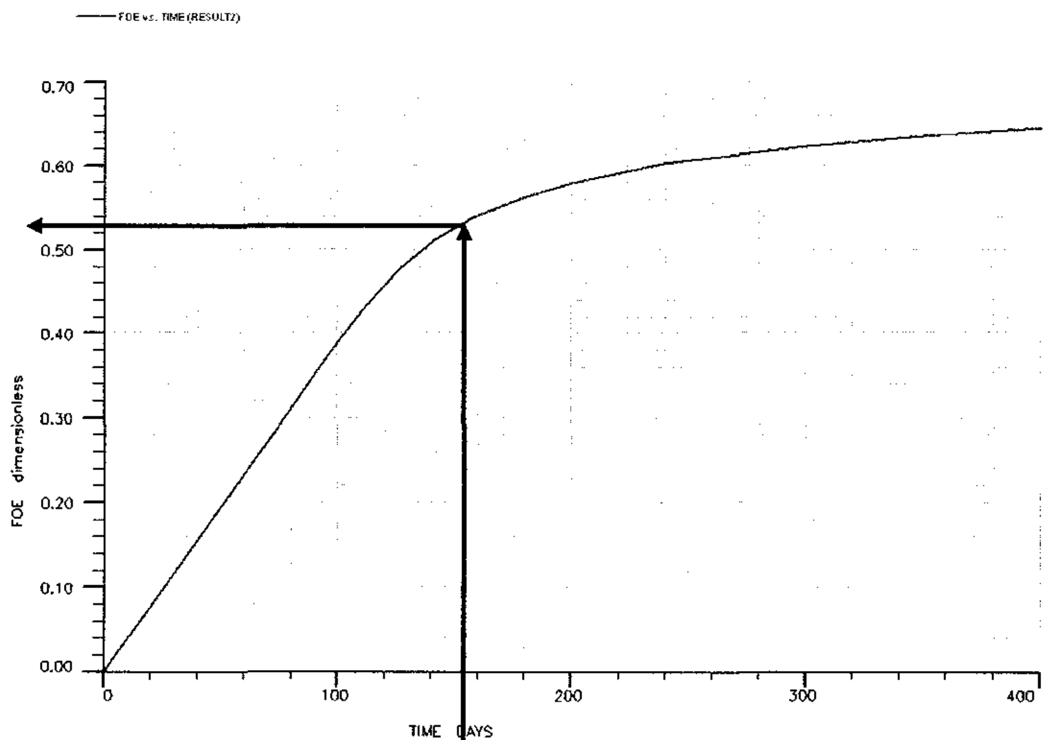

Figure 26: FOE versus Time (Base Case for Field)

Then, performances of the waterflooding analysis are refined by same analysis for the each layer available in Waha formation. For layer 1 (k=398md), the breakthrough time can be determined as 130 days and oil produced is 74,000 STB.

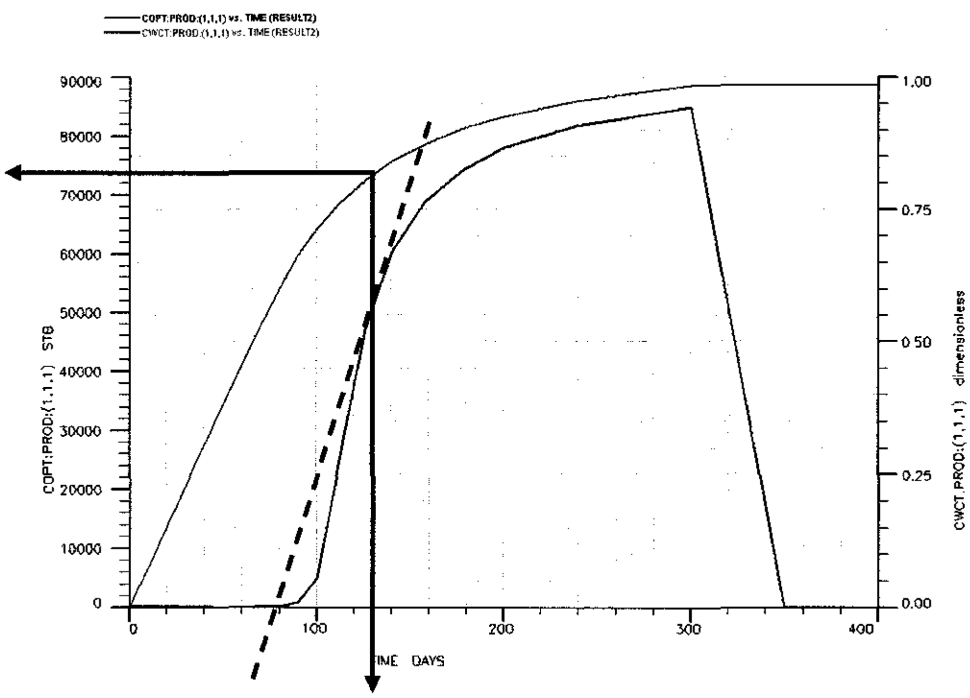

Figure 27: Oil Production and Water Cut for Layer 1

For layer 2 (k=225md), the breakthrough time can be determined as 155 days and oil produced is 205,000 STB.

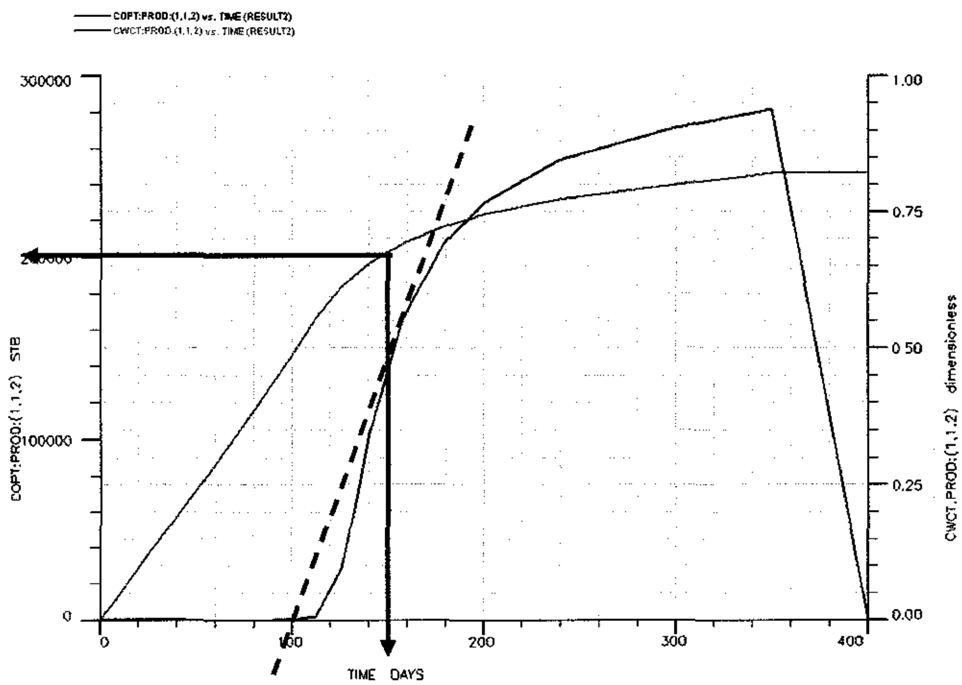

Figure 28: Oil Production and Water Cut for Layer 2

For layer 3 (k=95md), the breakthrough time can be determined as 190 days and oil produced is 30,000 STB.

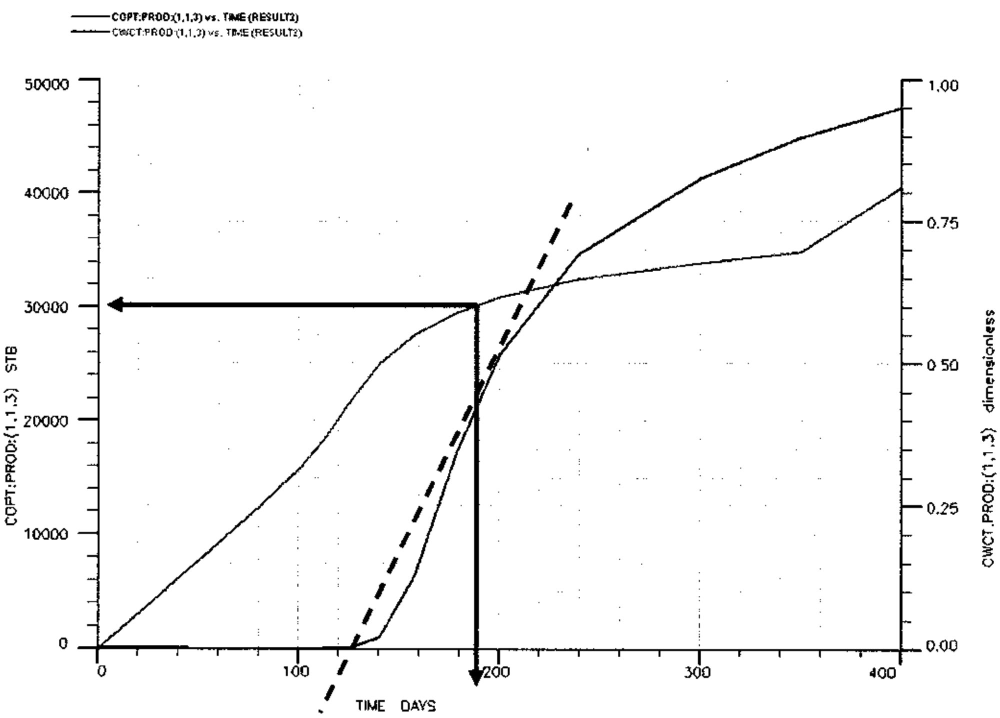

Figure 29: Oil Production and Water Cut for layer 3

Layer	Breakthrough Time (days)	Oil Produced (STB)
1	130	74,000
2	150	200,000
3	190	30,000

Figure 30: Summary of Waterflooding Performance for each layer (Base Case Model)

4.2 EFFECTS OF MOBILITY RATIO

The effects of the mobility ratio on the waterflooding performances can be seen by plotting the FWCT versus Time curves and FOE versus Time curves for all mobility ratio used in the simulation. From the curves, we can determine the breakthrough time and the oil recovery factor for the two other different mobility ratios.

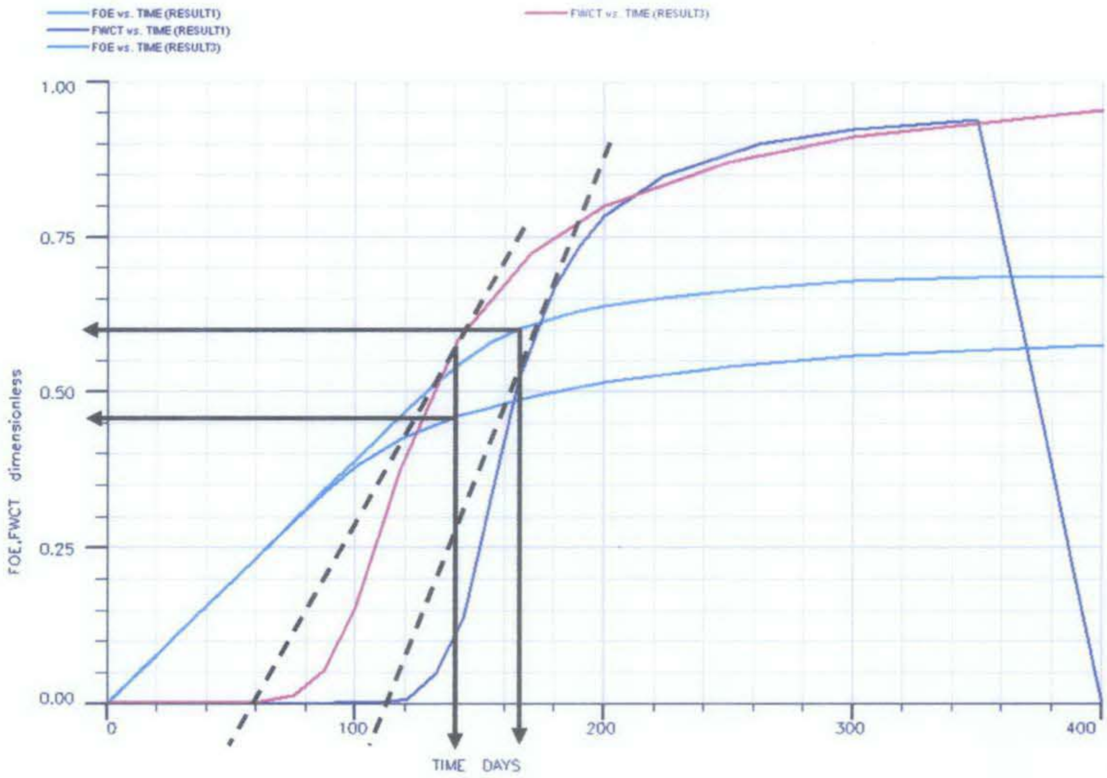

Figure 31: Oil Recovery Factor and Water Cut (M=0.5 and 2.0)

Mobility Ratio	Oil Recovery @ Breakthrough	Breakthrough Time (days)
0.5	0.60	165
1.0	0.53	155
2.0	0.46	140

Figure 32: Table of Waterflooding Performances for three mobility ratios

The performances of the waterflooding analysis are refined by same analysis for the each layer available in Waha formation. For layer 1 (k=398md), the breakthrough time and oil produced can be determined for mobility ratio equal to 0.5 and 2.

Figure 33: Oil Produced and Water Cut for layer 1 (M=0.5 and 2)

For layer 1, the effect of mobility can be compared in the table.

Mobility Ratio	Breakthrough Time (days)	Oil Produced (STB)
0.5	145	84,000
1	130	74,000
2	110	63,000

Figure 34: Summary of Waterflooding Performance for layer 1

For layer 2 (k=225md), the breakthrough time and oil produced can be determined for mobility ratio equal to 0.5 and 2.

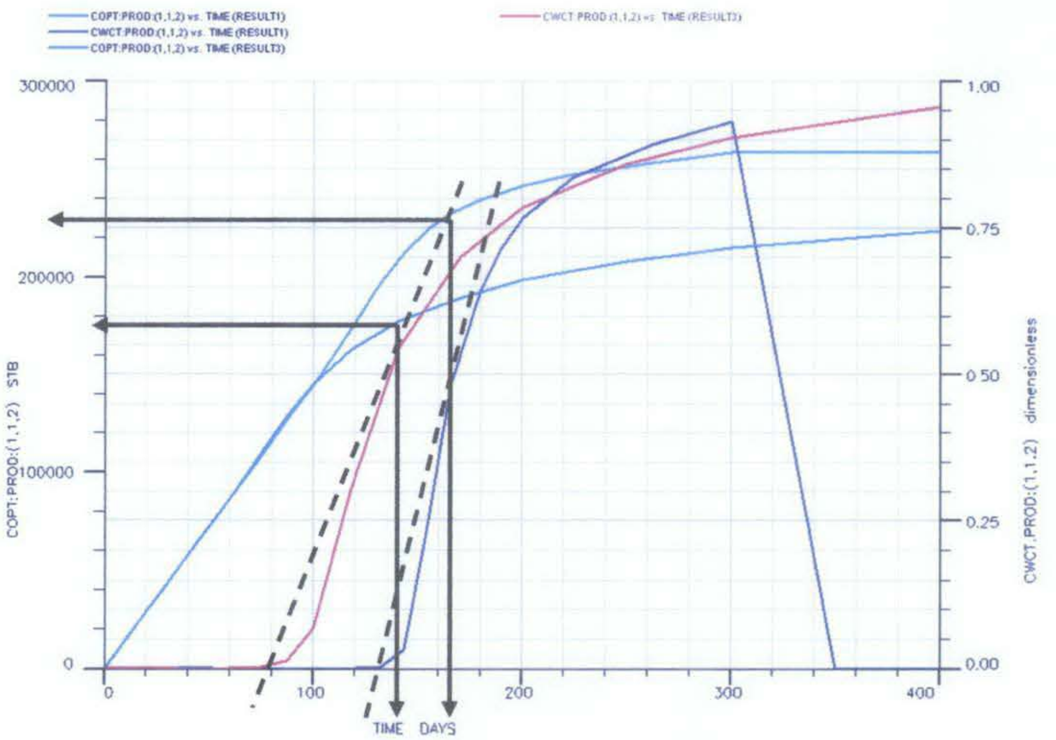

Figure 35: Oil Produced and Water Cut for layer 2 (M=0.5 and 2)

For layer 2, the effect of mobility can be compared in the table.

Mobility Ratio	Breakthrough Time (days)	Oil Produced (STB)
0.5	165	230,000
1	150	200,000
2	140	175,000

Figure 36: Summary of Waterflooding Performance for layer 2

For layer 3 (k=95md), the breakthrough time and oil produced can be determined for mobility ratio equal to 0.5 and 2.

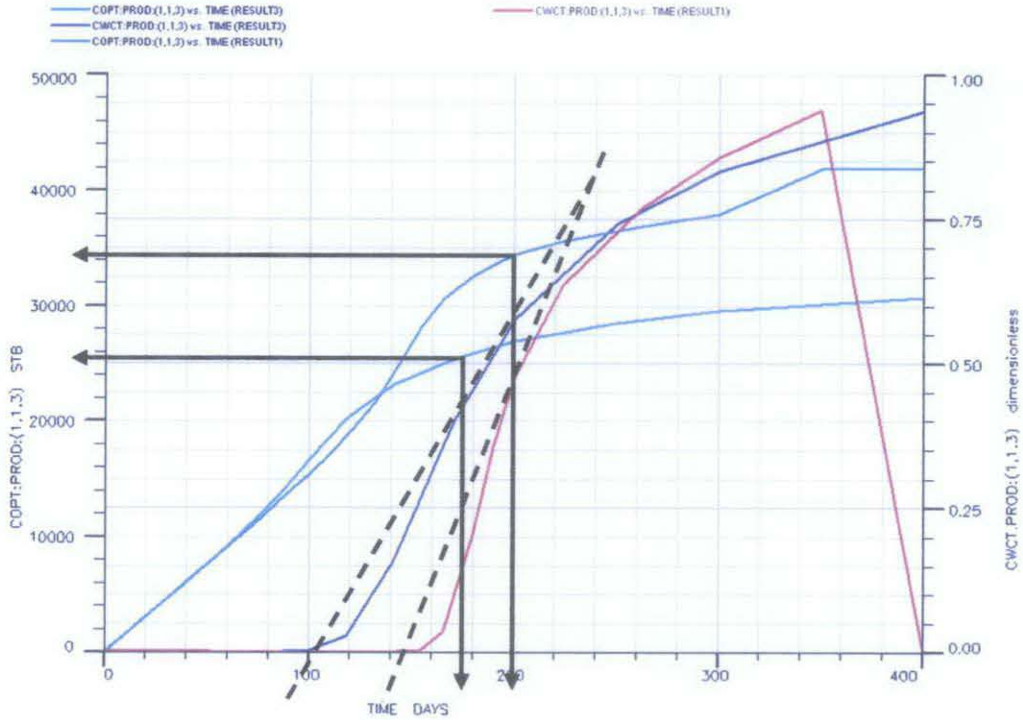

Figure 37: Oil Produced and Water Cut for layer 3 (M=0.5 and 2)

For layer 3, the effect of mobility can be compared in the table.

Mobility Ratio	Breakthrough Time (days)	Oil Produced (STB)
0.5	200	34,000
1	190	30,000
2	175	25,000

Figure 38: Summary of Waterflooding Performance for layer 3

Simulated results shown that high oil recovery can be achieved by mobility ratio equal to 0.5, followed by mobility ratio equal to 1 and mobility ratio equal to 2. Based on the equation, mobility ratio equal to 0.5 indicates that the velocity of the oil is double than the oil. As water is moves slower than the oil, the displacement process occurred is similar to the piston-like movement (water front will always remains behind the oil), in which the more oil can be displaced and no oil was left behind.

In case of mobility ratio equals to 2, the velocity of the water is double than the velocity of oil. As the water is moves slower than the oil, the displacement process occurred is similar to the fingering-like movement, in which the water will tends to bypass the oil during the displacement, resulting in less oil displaced. The oil that has been bypass will be trapped in the porous medium.

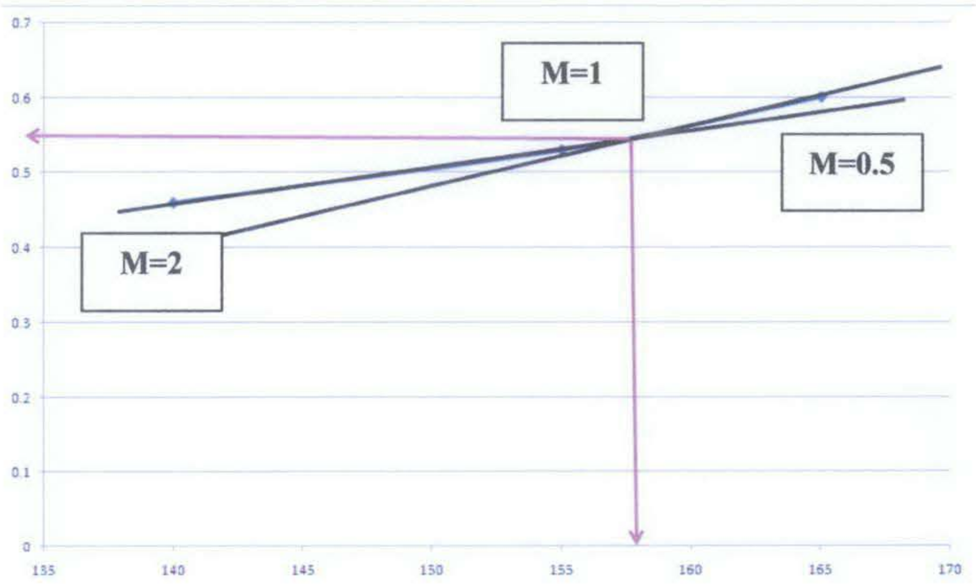

Figure 39: Graph Oil Recovery Factor versus Breakthrough Time

Based on the graph above, we can see that the behavior that optimum condition for this waterflooding project results in 0.55 oil recovery factor, with 158 days to achieve the breakthrough. Exact mobility ratio to produce this 'optimum' waterflooding performance is cannot be determined, but it can be estimated at mobility ratio at 0.8 (based on the behavior of the graph).

4.2 EFFECTS OF RESERVOIR HETEROGENEITY

The effects of the reservoir heterogeneity on the waterflooding performances can be seen by plotting the FWCT versus Time curves and FOE versus Time curves for two models used in the simulation. From the curves, we can determine the breakthrough time and the oil recovery factor for the homogeneous model.

The properties of the layers are modified into a constant permeability, 225 md while others parameters are remain the same.

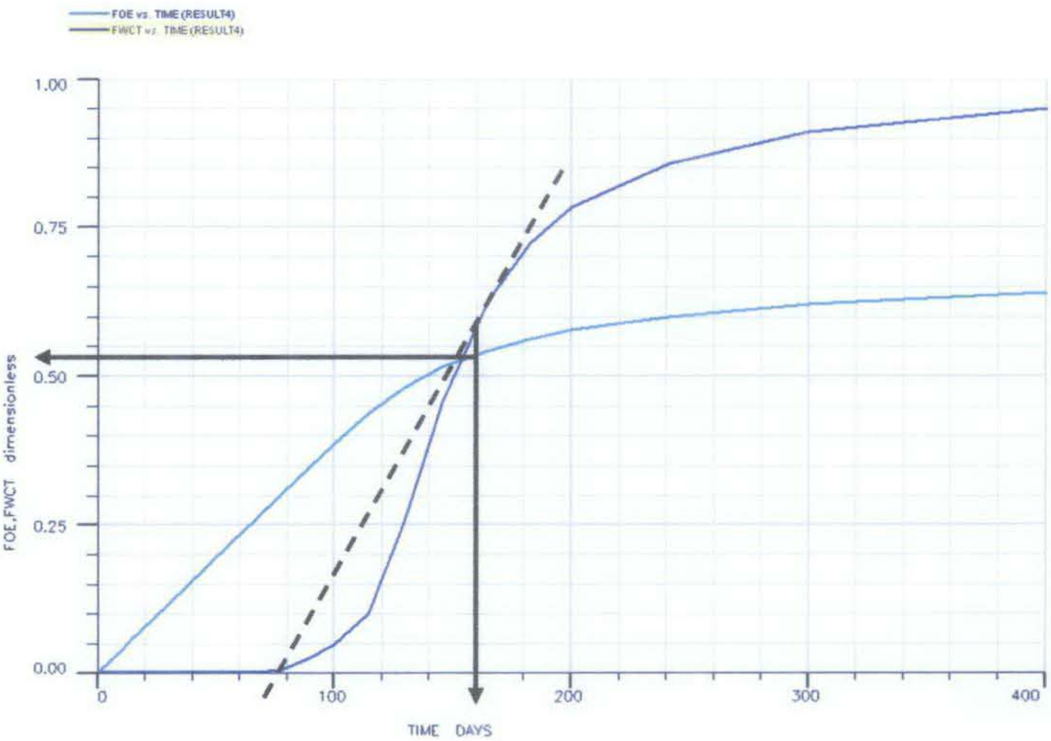

Figure 40: Oil Recovery Factor and Water Cut for Homogeneous Model

Model	Breakthrough Time (days)	Oil Recovery @ Breakthrough
Heterogeneous	155	0.53
Homogeneous	160	0.51

Figure 41: Comparison Table for two different models

The performances of the waterflooding analysis are refined by same analysis for the each layer available in Waha formation. For all layers, the breakthrough time and oil produced can be determined for the homogeneous model.

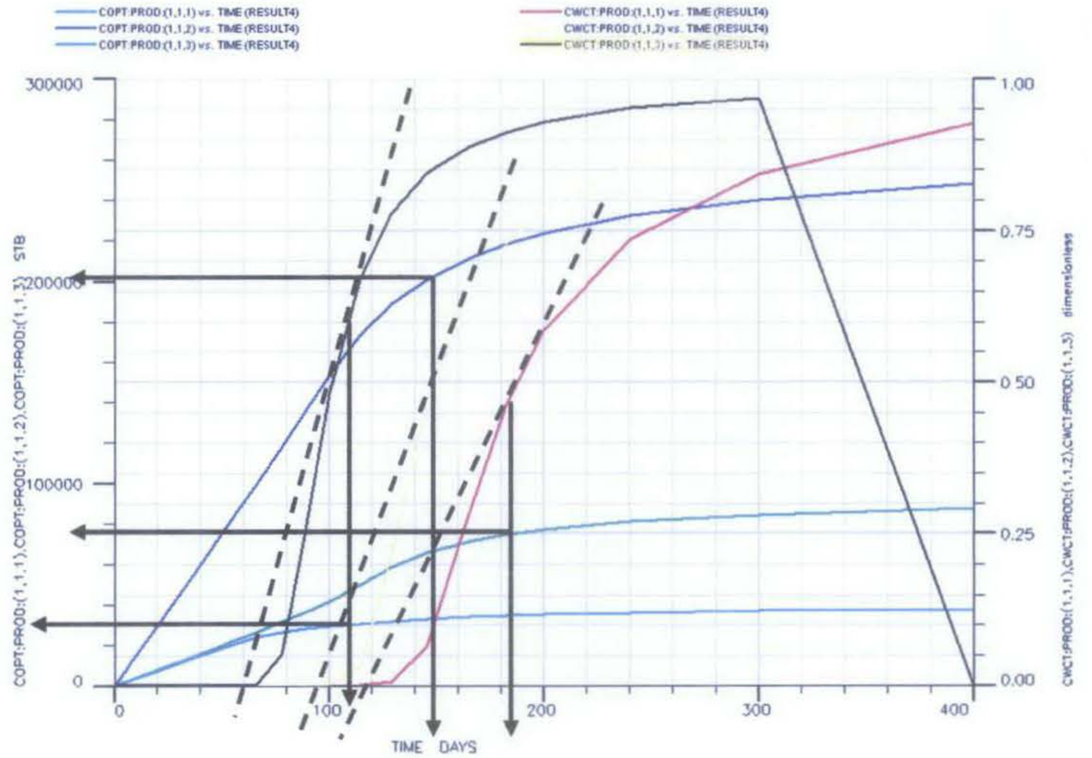

Figure 42: Oil Production and Water Cut for all layers (homogeneous model)

Layer	Model	Breakthrough Time (days)	Oil Production (STB)
1	Heterogeneous	130	74,000
	Homogeneous	185	75,000
2	Heterogeneous	150	200,000
	Homogeneous	150	200,000
3	Heterogeneous	190	30,000
	Homogeneous	110	30,000

Figure 43: Comparison Table for two models

In the layer 1, the heterogeneous model (k=398 md) was observed to produce less oil (74,000 STB) at earlier time (130 days), while the homogeneous model (k=225 md) was observed to produce more oil (75,000 STB) at later time (185 days), given the same value of mobility ratio (M=1).

This indicates that fluid travels faster in higher permeability formation, enabling an earlier breakthrough compared to lower permeability formation. However, due to the higher velocity of the displacement, the mobility ratio value might be increased, resulting of some oil left behind during the displacement.

In the layer 2, the heterogeneous model and homogeneous model have the same permeability value (k=225 md). The heterogeneous and homogeneous model was observed to produce same quantity oil (200,000 STB) at same time (150 days). This is due to the fact that both of the formation had the same value of permeability.

In layer 3, the heterogeneous model (k=95md) was observed to produce the same amount of oil (30,000 STB) with the homogeneous model, but at later time (190 days). The homogeneous model (k=225 md) was observed to produce the same amount of oil at earlier time (110 days).

This indicates that fluid travels faster in higher permeability formation, enabling an earlier breakthrough compared to lower permeability formation. However, low variation of permeability, affecting the lower changes in mobility value. In addition, the maximum volume of oil available in that formation makes the changes in mobility ratio insignificant.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

As a result of simulation study of the impact of mobility ratio on multilayered reservoir during waterflooding process, the following conclusions can be drawn:

- Mobility ratio less than 1 (**M<1**) results in more oil recovery but, at late breakthrough time.

- Mobility ratio more than 1 (**M>1**) results in less oil recovery but, at early breakthrough time.

- **High permeability** layer will affecting the mobility ratio, in which it increases the mobility ratio, results in less oil recovery at early breakthrough.

- **Low permeability** layer will affecting the mobility ratio, in which it decrease the mobility ratio, results in more oil recovery at late breakthrough.

- In the Waha formation, the simulated results suggested that mobility ratio equal to 0.8 (M=0.8) will **optimize** the waterflooding performances, given that the permeability variation is 0.4 (V=0.4).

5.2 RECOMMENDATIONS

In this study, several recommendations can be made to improve the accuracy of this study and suggested idea for the future works. The recommendations are listed as the following:

- The scope of the study should be improved from quarter of Five-Spot Pattern, to **a Five-Spot Pattern**. This will improves the accuracy results of our displacement, as this study assumed that quarter of Five-Spot is sufficient to superpose the other three quarter of Five-Spot Pattern.

- The scope of the mobility ratio should be improved, with increased number of **variables in mobility ratio**, instead of only three. This will enables the study of the mobility ratio behavior can be conducted, in which exact estimation of mobility ratio that provides optimum waterflooding performances can be estimated.

- The scope of reservoir heterogeneity should be improved, with increased number of **variables in permeability variation**, instead of only two. This wills enables the study of the permeability variation can be conducted, in which exact effect of permeability variation towards the mobility ratio and waterflooding can be studied further.

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APPENDICES

APPENDIX 1: WAHA RESERVOIR PROPERTIES

Distance between the injection and the producing wells (ft)	933
Five-spot area (acre)	10
Average reservoir thickness (ft)	79
Average reservoir porosity	0.19
Initial water saturation	0.153
Residual oil saturation	0.21
Total reservoir production (Rb/Day)	2270
Initial reservoir pressure (psia)	3390
Current reservoir pressure (psia)	2489
Reservoir temperature (^{O}F)	210
Rock compressibility (psi^{-1})	$3X10^{-6}$
Water compressibility (psi^{-1})	$3.43X10^{-6}$
Oil gravity (API)	37^{O}
Reservoir depth (ft)	7100
Water viscosity (cp)	0.27
Oil viscosity (cp)	0.423
Initial water saturation	15.3
Initial gas saturation	16

Figure 44: Average Reservoir and Fluid Properties

Layer	Average Porosity	Average Permeability	Thickness	Pore Volume
1	26.6%	398md	14ft	202MSTB
2	20.0%	225md	52ft	572MSTB
3	12.0%	95md	13ft	86MSTB

Figure 45: Reservoir Properties for each layer

Pressure (psia)	Oil Formation Volume Factor (RB/STB)	Oil Viscosity (cp)	Solution Gas-Oil Ratio (SCF/STB)
114.700	1.08213	1.29431	0.01690
501.781	1.12191	0.94007	0.10000
583.121	1.13167	0.88866	0.11984
1051.54	1.19452	0.68187	0.24385
1519.96	1.26678	0.56046	0.38010
1988.38	1.34686	0.48040	0.52537
2307.43	1.40536	0.43970	0.62854
2489.03	1.43370	0.42335	0.67788
2925.23	1.52683	0.38043	0.83650
3390.12	1.62050	0.34680	1.00040
3862.07	1.72941	0.31972	1.16906

Figure 46: PVT Properties

Water Saturation	Oil Relative Permeability	Water Relative Permeability
0.153	0.980	0.000
0.200	0.700	0.009
0.250	0.510	0.020
0.300	0.390	0.040
0.350	0.280	0.070
0.400	0.190	0.110
0.450	0.130	0.160
0.500	0.087	0.216
0.550	0.060	0.280
0.600	0.037	0.350
0.650	0.020	0.420
0.700	0.012	0.500
0.750	0.005	0.580
0.790	0.000	0.630

Figure 47: Water Saturation and Relative Permeability