Simulation Study on Optimizing Water-Alternating-Gas Carbon Dioxide (WAG-CO_2) Injection Parameters for Reducing Asphaltene Precipitation in Light Oil

by

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14248

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Petroleum Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

____

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2014

CERTIFICATION 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 reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MAGDELENE LEE JIA WERN

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ABSTRACT

Water-alternating-gas (WAG) is a popular enhanced oil recovery (EOR) method widely practiced in maximizing residual oil production. However, asphaltene precipitation during water-alternating-gas carbon dioxide (WAG-CO_2) injection is identified to be problematic in terms of reservoir flow assurance in light oils. Optimization of WAG process requires comprehensive understanding in WAG ratio, WAG cycle time and water injection rate. The simulation study using Eclipse 300 is suggested to perform optimization study on these WAG parameters during WAG-CO_2 injection in reducing the deposited asphaltene. The optimized WAG model in considering the proposed WAG parameters is aimed to be acquired in WAG-CO_2 process to minimize asphaltene precipitation and promoting more hydrocarbon production. A synthetic reservoir model with pre-defined reservoir properties and asphaltene description is prior to set up before generating two base models in further investigating the impact of the WAG parameters on oil recovery. The base models are WAG model with asphaltene and without asphaltene content. Each parameter is generated with a few options to obtain the best value during optimization phase. Field Oil Production Total (FOPT) is the output of simulation study, representing the recovery performance of WAG process in light oils under different scenarios. WAG ratio of 1 to 1, WAG cycle time of one month and water injection rate of 10000 bbl/day are the best recorded value for the WAG parameters. Higher value of each parameter is not always proportional to the oil can be produced from the reservoir. Using simulation study, WAG model without asphaltene content performs better in acquiring higher oil production than WAG model with asphaltene. It is related to the pore throat blockage of asphaltene in causing permeability reduction of reservoir when miscible carbon dioxide gas injection destroys the stability of asphaltene-resin micelles.

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CHAPTER 1: INTRODUCTION

1.1 Background

Petroleum is an essential resource in daily life. Initially when hydrocarbon within the earth layer has not been extracted, natural drive mechanisms such as water drive, solution gas drive and gas cap drive serve as the primary recovery techniques, producing 20% to 30% of the oil (Tunio *et al*., 2011). Secondary oil recovery uses mechanical energy which is not originated from the reservoir for pressure depletion strategy after oil production at the first production phase, maintaining the pressure in reservoir for further oil extraction (Dicke, 1944). The recoverable oil can reach up to 40% for secondary oil recovery methods. Some of the methods include water injection and gas injection.

Gas injection is widely applied in the field to extract more hydrocarbons. Selection of gas type for injection depends on the reservoir fluid to be produced. A variety of gas can be used, such as carbon dioxide, nitrogen, hydrogen sulphide, natural gas, produced gas from separator and rich gas. As for the purpose of using gas injection, it is also determined by reservoir fluid type in reservoir.

Gas condensate reservoir deploys gas injection for pressure restoration and mitigating the growth of retrograde condensates within the oil column (Adyani *et al*., 2011). Hydrocarbon reservoir adopts either miscible or immiscible gas in displacing the remaining oil. In immiscible gas displacement process, hydrocarbon is not only being displaced by the injected gas but also shedding away the lighter hydrocarbon constituents as produced fluid. In the other hand, miscible gas injection involves the dissolution of carbon dioxide into the crude oil, saturating the crude oil for a viscosity reduction. This eases the sweeping efficiency of residual crude oil, increasing the recovery factor of the concerned reservoir.

1.2 Problem Statement

The miscible gas flooding during WAG injection into the oil reservoir can possibly improve the recovery factor (Kokal & Sayegh, 1995). However it leads to the flocculation of asphathelne, as a result of compositional change (Moqadam *et al.*, 2009), significantly affects the reservoir's production profile during the phase of oil recovery. The rapid change in crude oil composition is referring on the intrusion of carbon dioxide gas which further enriching the reservoir as a light constituent of oil (Yonebayashi *et al.,* 2009). This has attributed to the modification in flow and phase behavior of reservoir, mentioned by Shelton & Yarborough (1977).

Gholoum *et al.* (2003) stated that CO_2 gas is effectively causing asphaltene precipitation followed by alkanes group (C_1 – C_7). Consequently, asphaltene precipitated on the pore spaces causes variation of rock wetting state, unfavour the performance of WAG. In addition formation damage in the wellbore zone, defect in failure functioning of equipment, plugged tubular pipes and surface facilities by asphaltene deposition leads to the reduction of oil throughpit (Becker, 1997).

The phenomenon of asphaltene precipitation in light oil reservoir is common, identified by de Boer *et al*. (1995) because light oil comprises more insoluble saturates such as n-alkanes, restricting the asphaltene solubility. Heavy oil contains good asphaltene solvents where presence of aromatic element like toluene dissolves asphaltene, hence the problem of reduced permeability by asphaltene precipitation is not noteworthy.

1.3 Objective

The objectives of this simulation study are:

1. To determine the effect of water-alternating-gas (WAG) technique towards asphaltene precipitation in light oil.
2. To investigate the best case WAG parameters in maximizing oil recovery.

1.4 Scope of Study

The overarching purpose of the simulation study is to assess the factor of WAG ratio, WAG cycle and water injection rates in contributing an ultimate oil production in a light oil reservoir when the problematic asphaltene precipitation can be minimized.

Using the means of simulation study with Eclipse, a synthetic reservoir model is built with defined properties. Two base models, WAG model with asphaltene and without asphaltene are constructed to evaluate the effect of changing these three parameters on Field Oil Production Total (FOPT). FOPT will be the main output in determining the best WAG design in optimizing the oil production.

CHAPTER 2: LITERATURE REVIEW AND/OR THEORY

2.1 Enhanced Oil Recovery (EOR)

Tertiary oil recovery has a common name of enhanced oil recovery (EOR). EOR is a prevalent method covering a wide range of processes in maximizing hydrocarbon extraction. It is considered when the oil production from maturing fields by the means of conventional recovery is insufficient in meeting the growing demand of this energy (Kokal & Al-Kaabi, 2010). Immobile oil within the reservoir will now be the target of EOR technology, substantially recovering an additional of 60% to 65% of hydrocarbons.

Energy Department in U.S.A. posited that total oil volume has been extracted occupies only one third of the available oil globally. The remaining oil (two third of petroleum resource) is the potential reservoir product of EOR technique. A total of nearly 707,000 barrels of oil per day (BOPD) is extracted in U.S. using EOR method in 1998. Thermal EOR, miscible and immiscible gas EOR occupy more than 99% of oil production using EOR technologies in U.S. Chemical EOR and microbial EOR are at the research phase for implementation, claimed in Tunio *et al.* (2011). However, Abdi *et al.* (2014) stated that the current trend in the development of EOR methods is on chemical injection.

2.2 Water-Alternating-Gas (WAG)

WAG injection is an EOR method combining two conventional practices, which are water flooding and gas injection to enhance hydrocarbon production profile. The alternate injection of water and miscible gas into the upswept zone displaces the attic and cellar remaining oil. The theory of WAG injection explains lighter gas opposes the gravity force and segregates upwards while heavier water accumulates on the bottom (Srivastava & Mahli, 2012). WAG method is fully utilizing the flow behavior adhered by both water and gas to provide an ultimate recovery of hydrocarbon, mentioned in Freistuhler *et al.* (2000) and Soares (2008). Mechanism of WAG illustrates better microscopic displacement of gas aided by macroscopic sweep of water when mobility control of gas is taken over by water, leading to a more frequent contact to residual oil and increase sweeping efficiency.

Most of the fields in the United States practices WAG injection as the preference EOR method in miscible gas condition, stated in Kulkarni & Rao (2005). The first application of WAG injection is practiced by Exxon Mobil in recovering a field which has just undergone water flooding in 1959. According to Nangacovié (2012), miscible process during WAG injection can be altered by optimizing the WAG process. Miscible gas is injected to dissolve the residual oil in Alberta field, leading to more oil recovered (Rogers & Griggs, 2001). Miscible gas condition provides an addition of 60% to 70% of extracting the potential oil out of reservoir. Existence of miscible gas exploits the advantage of oil viscosity in mobilizing the trapped oil during later stage of production. Variety choices of miscible gas are used in suiting different reservoirs of distinct characteristic.

Almost 90% of the studied field uses carbon dioxide (CO_2) or hydrocarbon gas as the source of miscible gas injection. Carbon dioxide is preferably selected (47%) as the gas used in WAG injection, followed by 42% recorded by hydrocarbon gas (Rogers & Grigg, 2001). Srivastava & Mahli (2012) reported that carbon dioxide is a better choice of gas in improving oil recovery when the result of higher hydrocarbon pore volume (HCPV) (40.18%) is recorded by carbon dioxide, comparing with merely 19.35% of HCPV by hydrocarbon gas during five cycles of WAG injection.

59 fields are reviewed by Christensen *et al*. (1998) in implementing WAG scheme in further optimizing the field potential in producing more hydrocarbons, especially those fields that are located in Canada and USA. Rao (2001) expressed the dissatisfaction on the ineffectiveness of WAG injection as majority of the WAG application fields are reported low recoveries (5% to 10% of Original Oil in Place (OIIP)). The incomprehensive study of the WAG scheme has leads to the failure of

its performance, speeding up the early breakthrough of injected fluid (Kulkarni & Rao, 2005).

Feasibility study conducted in designing a WAG process on laboratory scale requires a comprehensive understanding on the parameters involved for efficient operation in sweeping the residual oil. The contributing factors include fluid properties, rock-fluid interactions, reservoir heterogeneity, WAG ratio, source and composition of injected gas and injection pattern. The prevailing condition of rock-fluid properties may vary with time, as the ongoing chemical reactions in reservoir can be unpredictable. Failure in adapting the fluctuation occurs resulted in variation of reservoir's wettability and inaccuracy of flow assurance factors such as capillary pressure and relative permeability (Zahoor, Derahman and Yunan, 2011).

Volume of gas needed for injection reduces in the WAG application, as compared to pure gas flooding. Laboratory study by Srivastava and Mahli (2012) has pointed out the significant of gas-oil-water phases in reservoir in recovering more residual oil.

2.3 Asphaltene

Asphaltene is a crude oil component with complex molecular structure, soluble in toluene but insoluble in n-alkanes. Within the n-alkanes group, n-heptane is defined to be containing more aromatics than n-pentane (Kokal & Sayegh, 1995), when both components are used to compare their respective composition in a precipitant solution. As a result, it is found that hydrocarbon ratio is lower in n-heptane, proving that it is a more insoluble solvent. Logically, n-heptane is selected to be the most insoluble solvent where asphaltene precipitation can be easily recognized. Nonetheless, a larger n-alkanes molecule do not precipitate asphaltene as much as smaller n-alkane component.

Asphaltene poses polarity characteristic and it appears as a colloidal deposit in crude oil. High polar resins are easily attracted by the charged asphaltene, fall on its surface and act as a shielding coat of asphaltene. The term micelles are used to describe this peptized component. This micelles are strongly bonded by a repulsive force exists between resins and asphaltene surface, flocculation will not occur.

(Alta'ee *et al.*, 2012). However, flocculent such as n-heptane will further destroy the asphaltene-resin molecules worsen the process of asphaltene to flocculate permanently. As long as the crude oil reservoir is kept in equilibrium state, asphaltene will not form into deposition on the rock surface.

2.4 Asphaltene Precipitation

Asphaltene suspension in stabilized state does not affect the production phase; it is unwanted and troublesome only when the asphaltene deposits obstruct the pore spaces available during oil sweeping process by injection fluids. Amount of asphaltene content in a reservoir is varied by several factors, for example source where asphaltene derived from, depth of burial deposition and API gravity of petroleum. The precipitation process is independent on the asphaltene content in a crude oil. A reservoir with 17 weight percent (wt%) of asphaltene fraction in Boscan field in Venezuela is less likely to face the problem of asphaltene precipitation when comparison is made with Hassi-Masoud field located in Algeria which has merely 0.15 wt% asphaltene but the severe problem is observed on asphaltene precipitation (Alta'ee *et al*., 2010).

The peptized micelles are potentially losing its stability during miscible CO_2 gas injection as crude oil composition is altered after the intrusion of CO_2 into the reservoir. Resin-to-asphaltene ratio is being affected and it increases the tendency in causing the asphaltene to precipitate. Asphaltene forms as a visible constituent in the liquid phase and this is when precipitation takes place (Khanifar & Darman, 2011). The separated, fines particles gradually clump into larger visible, distinctive lump. Flocculation explains this scenario happens in the crude oil. At last, deposition is significant when the large lumps settle out of the liquid phase and sit on the rock surface.

Buriro *et al*. (2013) discussed that pressure, temperature and composition within the reservoir are identified as the contributing factors affecting the instability of asphaltene-resin molecule. Besides that, carbon dioxide is of the crucial aspect in affecting the asphaltene stability. The amount and concentration of CO_2 gas being injected during WAG process is worth to be studied. Experiment performed in Srivastava *et al.* (1999) proves that the quantity of asphaltene precipitated is relatively increasing in accumulation with the pore volume and concentration of carbon dioxide.

Oil recovery can be generalized by the amount of CO_2 injected, stated in Kulkarni & Rao (2005) but Chukwudeme & Hamouda (2009) claimed that higher concentration CO_2 injection beyond its critical value increases the amount of asphaltene deposited. This has shown contradictory relationship among carbon dioxide, asphaltene precipitation and oil recovery. Implementation of injected gas concentration below the critical value in minimizing asphaltene precipitation in recovering more oil for production is recommended.

2.5 WAG Ratio

WAG ratio is an important parameter to be considered in designing a WAG scheme. Al-Shuraiqi *et al*. (2003) explained that under optimum WAG ratio condition water acts as a role of controlling the growth of viscous fingers. Number of pore volume injected is minimized while mobility contrast is provided (Juanes & Blunt, 2006). Christensen *et al*. (1998) has pointed out the poor result of WAG injection is partly contributed by the misjudgment of WAG ratio. Sensitivity analysis is performed in obtaining an optimum WAG ratio to examine its influence on oil recovery. Nominally, WAG injection of 1:1 is implemented in the field.

Different WAG ratio is applied depending on the rock wetting state of reservoir, availability of gas for injection, formation water and oil properties and geological characteristic. WAG ratio is one of the core concerns as the applied ratio is greatly relying on the wettability of reservoir (Jackson *et al.*, 1985) and the source of injected gas. In an oil-wet reservoir, larger portion of gas is preferred to be injected comparing to water.

Since more gas is intended to be injected when small WAG ratio is decided, the behavior of gas flooding could be observed where the production performance can be affected by rapid pressure declination, followed by early gas breakthrough (Wu *et al.*, 2004). There are also chances when the implementation of higher gas volume in a WAG process is not possible when economic constraint is restricting the installation of surface facilities such as compressors and pumps.

Tapering is a technique used in determining the optimum WAG ratio to be used in a field. It can be either increasing or decreasing the water to gas ratio injected during a flooding process. Since early 1960s, tapering is first applied on a WAG field. In the effort of preventing early breakthrough of injected gas in a WAG injection, increasing the water volume comparing to the gas volume is suggested (Christensen *et al*., 1998). However, as the oil saturation decreases over time, more gas volume is required to recover the residual oil, claimed in Jiang *et al.* (2010). In terms of economic concern, the idea of tapering came up with the reason of high cost in injecting large volume of gas during an EOR process.

2.6 WAG Cycle Time

WAG cycle time design often sticks back with the conventional practice in field application. Minute effect of WAG cyclic time neglects its modification for further enhancement in oil recovery. Simulation can be the platform to determine its impact on production profile, claimed in Pritchard & Nieman (1992).

WAG cycle time is referring how often is the switching of gas and water injection throughout a WAG process. According to Wu *et al*. (2004), the sequence manner for gas and water injection reflects the capability of gas storage. Each WAG cyclic pattern can be attempted to understand the effect of injecting slug volume of gas and water over a definite period on recovering more residual oil.

2.7 Water Injection Rate

Other than WAG ratio, optimizing the injection scheme can be a feasible hybrid technique to recover more oil production (Chen *et al*., 2009; Dang *et al*., 2014). Al-Shuraiqi *et al.* (2003) stated that oil recovery is a function of rate due to the changes in relative permeability. The impact of rate in WAG performance is related to capillary pressure which causes variation in the front displacement pattern. Capillary pressure is high when reduction of permeability is recorded.

Rate is expressed as an order of lower magnitude. Depending on the scale of field studied, rate effects can be negligible when capillary pressure is dominating the displacement front. In fact, rate does not have the direct relationship with the efficiency of miscible gas displacement. Rate can be altered to suppress viscous fingering effect.

2.8 Summary of Literature Review

WAG is an EOR approach suggested to enhance the pure gas flooding mechanism, which is found to be delaying in production. Water injection performed after gas injection improves gas displacement efficiency when the gas mobility is reduced. Flow behavior of gas and water during WAG injection displace the top and bottom residual oil. This two-phase injection is claimed to be more efficient in improving tertiary oil recovery, supported by experimental investigation by many researchers. Not all oil fields in Canada and USA show satisfactory oil recovery as the knowledge on rock-fluid interaction is not comprehensively studied. Other than rock and fluid properties, WAG ratio is also a contributing factor to the reservoir wettability and relative permeability curves. WAG ratio of 1:1 is usually practiced. During WAG injection, it reduces the amount of CO_2 gas required, lesser than what required in pure gas flooding. Asphaltene is easily attracted to resin to form micelles in the crude oil. It is not a problematic issue when there is sufficiently high content of asphaltene in a reservoir. However, intrusion of miscible CO_2 destroys this stabilized component, leading to an unwanted occurrence which is asphaltene precipitation. The steps involved are precipitation, flocculation and deposition. The greater the gas concentration, asphaltene precipitation is more severe. Hence reducing CO_2 solubility in crude oil is necessary in avoiding deposition of asphaltene on the pore spaces. There are many factors involved in optimizing the WAG process for maximizing oil recovery, such as WAG ratio, WAG cycle time and water injection rate. Optimization of these WAG parameters should not be neglected and it should be studied to study its impact on oil recovery.

CHAPTER 3: METHODOLOGY/PROJECT WORK

3.1 Methodology

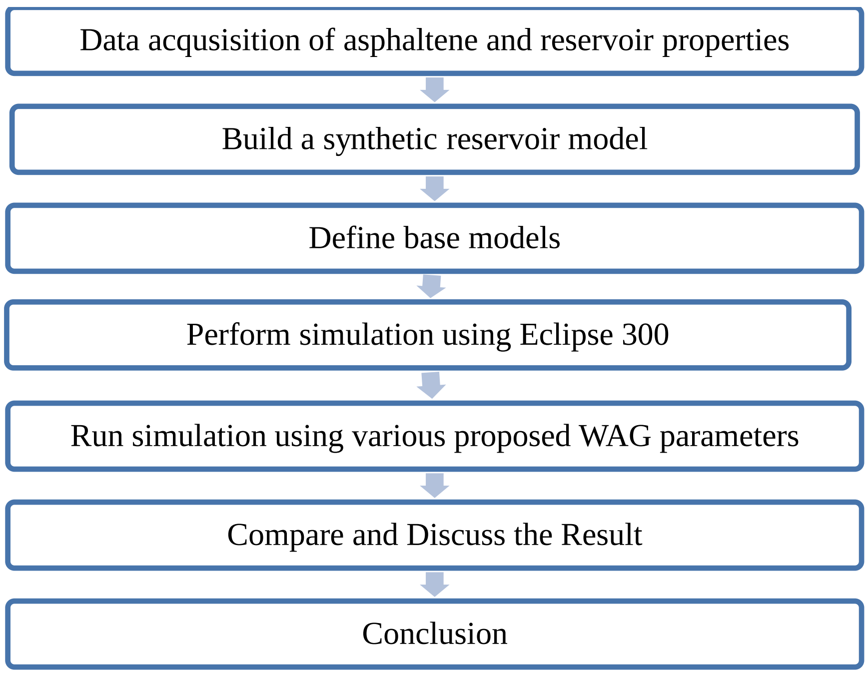

Figure 1 : Sequence of works involved in Simulation Study

To begin with a simulation approach, acquisition work in obtaining the feasible type of asphaltene with reasonable reservoir properties from a field data is required. It is intended that dataset from Eclipse 300 is adhered. A synthetic reservoir model is constructed and the fluid properties are defined. The data has to be suitable for application in all simulation run. Then, two base models are established to compare WAG model with and without asphaltene content. Simulation procedure will be run in getting Field Oil Production Total (FOPT) as the output of simulation. Comparison will be made to see the difference of including asphaltene into a WAG model, see Table 1. Then, WAG ratio, WAG cyclic time and water injection rate are set to be the parameter to be examined in affecting the two base models. The output of FOPT will be tabulated as shown in Table 2, 3 and 4 for each parameter.

Table 1: FOPT of two base models

Run	**Base Model**	**Field Oil Production Total (FOPT) (STB)**
1	WAG model without asphaltene	
2	WAG model with asphaltene	

Table 2 : FOPT of different WAG ratio

Run	**WAG ratio**	**Field Oil Production Total (FOPT) (STB)**
1	1:1	
2	2:1	
3	3:1	
4	1:2	
5	1:3	

Table 3 : FOPT of different WAG cycle time

Run	WAG cyclic time (month)	Field Oil Production Total (FOPT) (STB)
1	1	
2	3	
3	6	

Table 4 : FOPT of different water injection rate

Run	Water Injection Rate (bbl/day)	Field Oil Production Total (FOPT) (STB)
1	5000	
2	10000	
3	30000	
4	65000	
5	80000	
6	100000	

3.2 Reservoir and Fluid Properties

Table 5: Description of reservoir and fluid properties

Properties	Description
Reservoir Size	10 x 10 x 3
Number of Components	7
Thickness (x-axis)	100 ft
Thickness (y-axis)	100 ft
Thickness of Layer 1 (z-axis)	20 ft
Thickness of Layer 2 (z-axis)	30 ft
Thickness of Layer 3 (z-axis)	50 ft
Permeability of Layer 1	500 mD
Permeability of Layer 2	50 mD
Permeability of Layer 3	200 mD
Gas Density	0.06054 lb/scf
Oil Density	49.1 lb/scf
Water Density	62.4 lb/scf
Porosity	0.3
Gas-Oil Contact	8200 ft
Oil-Water Contact	8500 ft
Bottom-hole Pressure	1000 psia
Reservoir Pressure	4800 psia
Well Diameter	0.5 ft
Location of Injector Well	(1,1,1)
Location of Production Well	(10,10,3)

3.3 Initial Reservoir Oil Constituents

Table 6 : Elements in initial reservoir oil

Element	**Percentage (%)**
C_1	0.500
C_3	0.060
C_6	0.000
C_{10}	0.200
C_{15}	0.150
C_{20}	0.090
Asphaltene	0.000

3.4 Illustration of the Synthetic Static Model

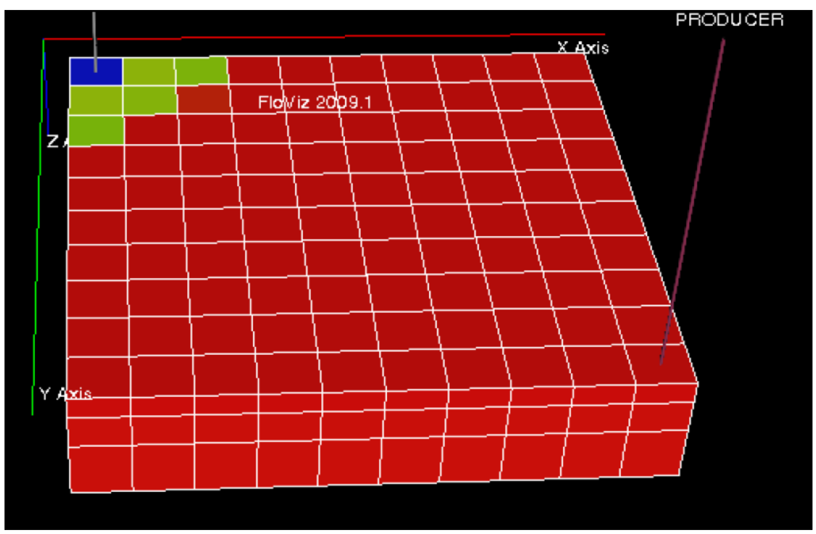

Figure 2: Image of synthetic static model constructed

3.5 Key Milestones

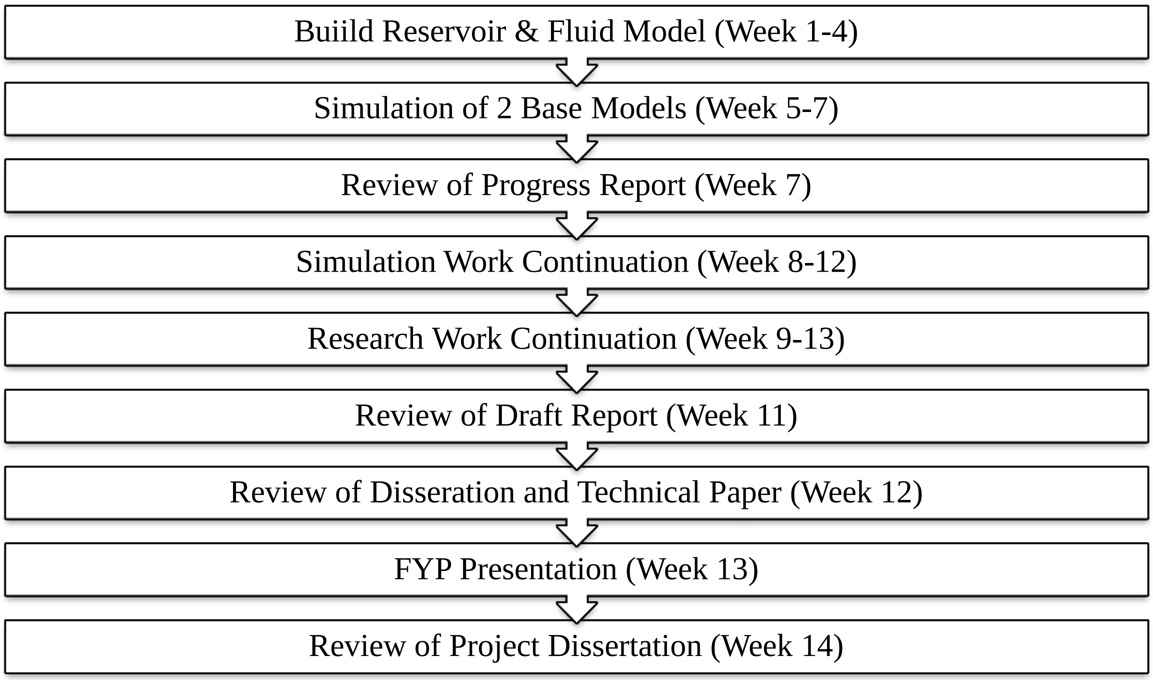

Figure 3 : Key indicators to complete a dissertation

3.6 Gantt Chart

Table 7: Gantt chart of simulation project

Description	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Planning														
- Gathering of information														
- Critical literature review of project														
- Eclipse familiarization														
2. Simulation Study														
- Construct a reservoir model with defined properties														
- Run simulation														
- Gathering of simulation results														
3. Analysis														
- Comparative study of the base models														
- Comparative study of different WAG parameters														
- Interpretation of findings														
4. Review														
- Check on the validity of results														
- Put into discussion														
5. Documentation														
- Compilation of findings														
- Complete a project dissertation														

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Overview

In this section, results from the simulation run will be presented in the form of graphs. Two base models: WAG model with asphaltene and WAG model without asphaltene is simulated to show the presence of asphaltene in affecting FOPT value (oil recovery). Then each WAG model is tested using different parameters in showing their effects on oil production. The parameter includes

1. Water injection rate
2. WAG ratio
3. WAG cyclic time

4.2 Base Model: WAG Model with and without asphaltene

<u>Indicator</u>

WAG model without asphaltene (orange line)

WAG model with asphaltene (magenta line)

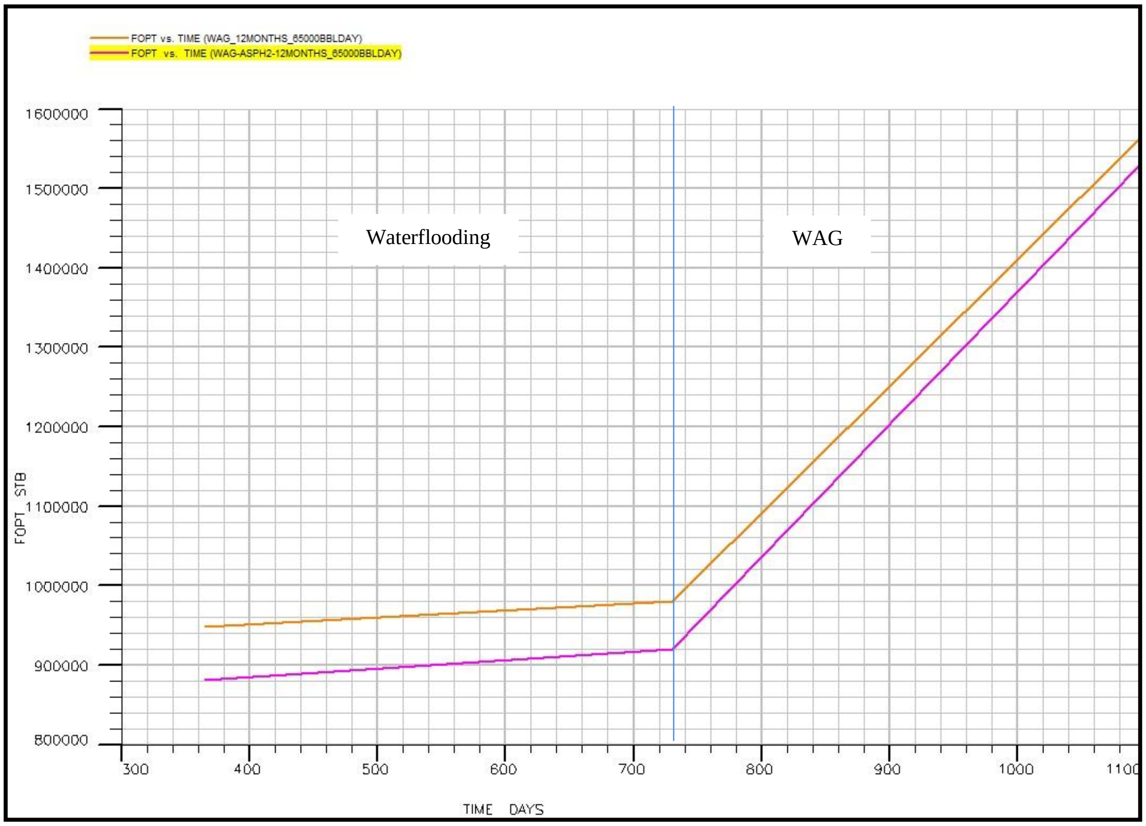

Figure 4 : Graph plotting FOPT vs. time for the base WAG models

Table 8 : FOPT of two base WAG models

Run	Base Model	Field Oil Production Total (FOPT) (STB)
1	WAG model without asphaltene	1560000
2	WAG model with asphaltene	1524000

Water-alternating-gas (WAG) scheme is tested on its production profile by placing two scenarios: WAG model with asphaltene and WAG model without asphaltene. In Figure 4, the almost horizontal line from 370^{th} to 730^{th} day represents the secondary waterflooding process. The graph plotted after 730^{th} day is showing the effect of tertiary EOR method, WAG injection. The linearly increasing of FOPT during WAG process indicates the efficiency of tertiary EOR in recovering more residual oil.

It is clearly showing a gap between the linearly increase lines of these two models, directing a higher oil sweeping efficiency of using WAG injection with no asphaltene precipitation (1560000 STB). A difference of 36000 STB is recorded between the models at 1090^{th} day. Table 8 shows the respective FOPT of two WAG models.

Adbi *et al*. (2014) posited that a significant rising in pressure difference is observed after asphaltene has deposited on the pore channel. Asphaltene starts losing its stability and precipitated asphaltene solid formed when more CO_2 gas dissolves into the oil column during WAG injection. Precipitated asphaltene obstructed the pore spaces of rock, causes a reduction in porosity and permeability. The reduction of permeability is followed by a lower flow rate of oil during production. It is explanatory with the formula shown in Equation 1.

$$k = \frac{q\mu \, dL}{A \, dP} \qquad \text{----} \quad eq. (1)$$

Therefore, it can be concluded that during a WAG process in the field, presence of asphaltene reduces the permeability of interconnected pathway for oil flow, affecting the flow assurance during oil production. Asphaltene precipitation should be minimized to promote efficiency of WAG injection as an effective EOR method.

4.3 WAG Models with varying Water Injection Rate

Indicator

Injection rate of 5000 bbl/day

Injection rate of 10000 bbl/day

Injection rate of 30000 bbl/day

Injection rate of 65000 bbl/day

Injection rate of 80000 bbl/day

Injection rate of 100000 bbl/day

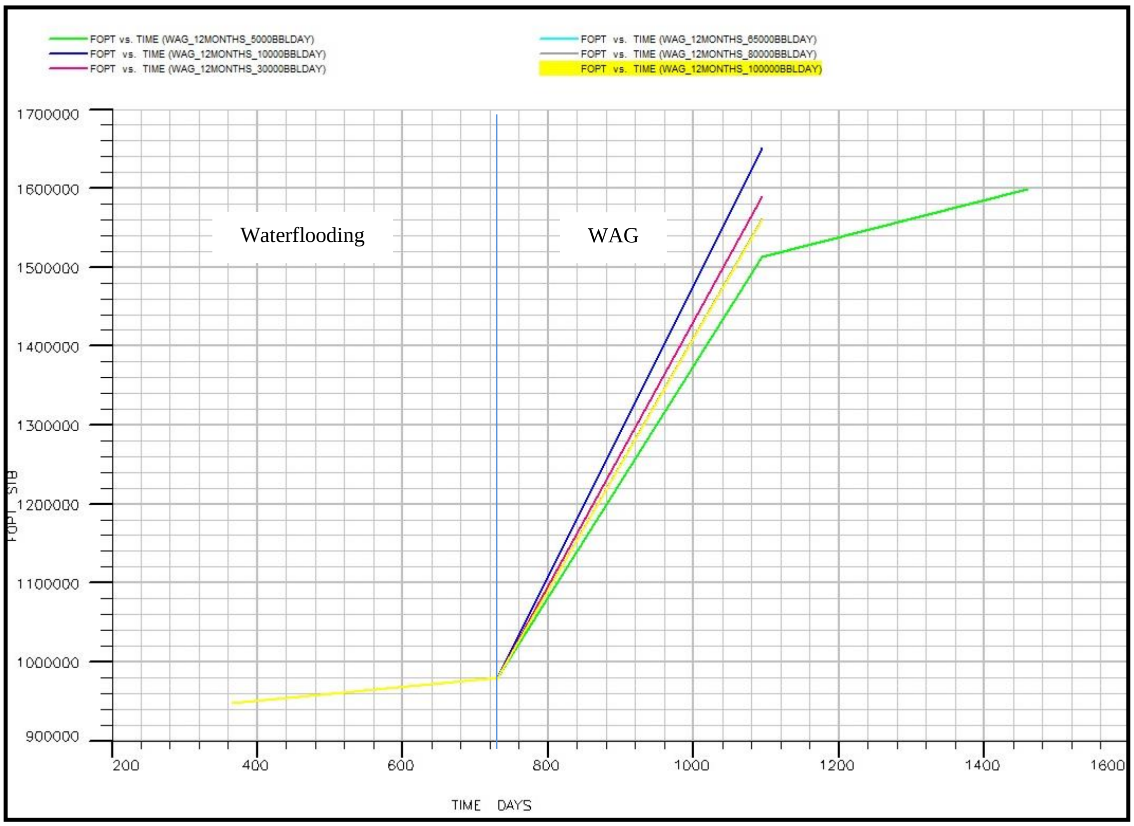

Figure 5 : Graph plotting FOPT vs. time for WAG model without asphaltene varying water injection rates

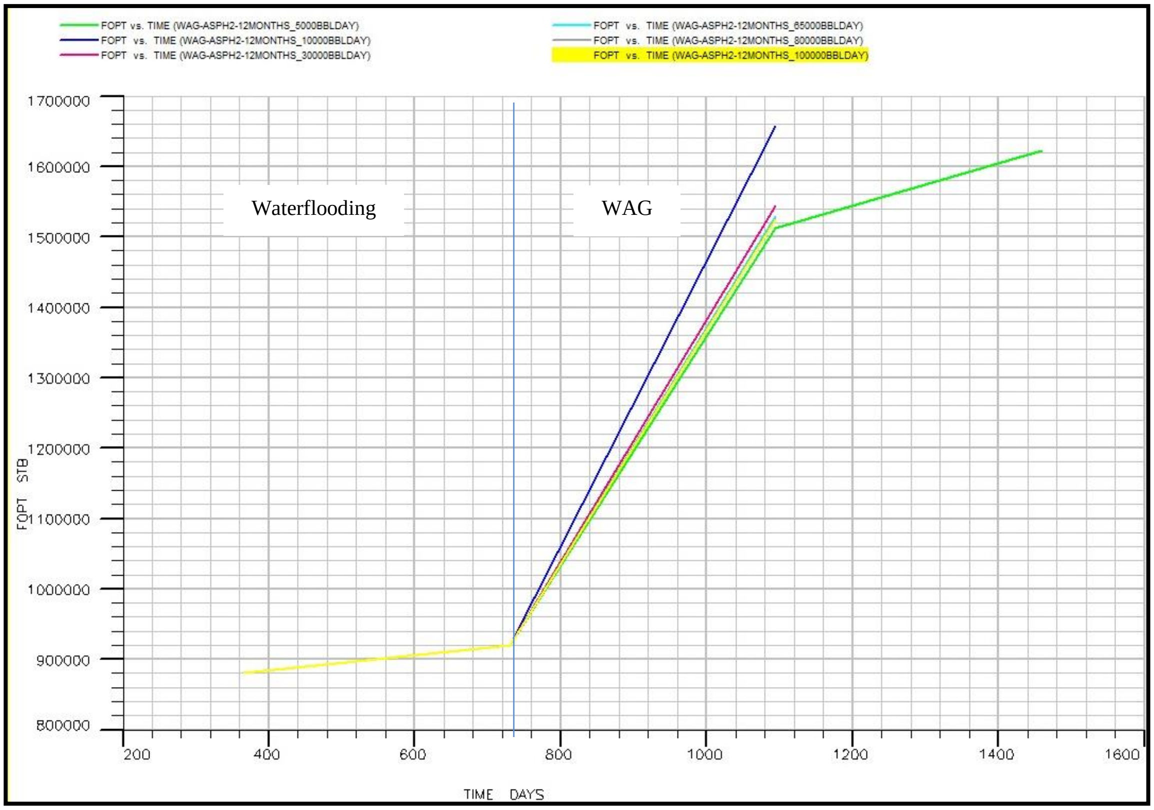

Figure 6 : Graph plotting FOPT vs. time for WAG model with asphaltene varying water injection rates

Table 9 : FOPT of WAG models with different water injection rate

Run	**Water Injection Rate (bbl/day)**	**Field Oil Production Total (FOPT) (STB)**	
		Without Asphaltene	**With Asphaltene**
1	5000	1600000	1620000
2	10000	1650000	1660000
3	30000	1590000	1545000
4	65000	1560000	1530000
5	80000	1560000	1530000
6	100000	1560000	1530000

To build an optimized WAG model in aiming to observe the reduction in asphaltene precipitation, the parameter water injection rate is first altered in evaluating the best water injection rate in showing the highest oil production. Base WAG models use 65000 bbl/day water injection rate. In this optimization phase, another five injection rates are generated, summing up with a total of six different injection rates to study the impact of water injection rate on oil recovery: 5000 bbl/day, 10000bbl/day, 30000bbl/day, 65000 bbl/day, 80000 bbl/day and 100000bbl/day.

In Figure 5, it can be observed that water injection rate of 10000 bbl/day resulted in a highest FOPT (1650000 STB). An additional of 60000 STB oil can be recovered comparing with 30000 bbl/day injection when a lower water injection rate (10000 bbl/day) is performed. As for water injection rates of 65000 bbl/day, 80000 bbl/day and 100000 bbl/day resulted with overlapping graphs to each other, show no variation of oil recovery. Lastly the lowest water injection rate of 5000 bbl/day displays the poorest production profile (1600000 STB). The process of whole oil recovery process takes a longer time than the other water injection cases, ended at the 1460^{th} day.

Figure 6 shows the result of total oil production when WAG model with asphaltene is input for simulation. A similar result is obtained which is injection of 10000 bbl/day is the best injection rate in WAG design of this simulation model. Table 9 has listed down the FOPT of each injection rate for both WAG models.

The amount of oil being recovered is not always proportional to the increment in water injection rate (Surguchev *et al.,* 1992). The effect of water injection rate is related on the reservoir heterogeneity. At a lower permeability layer increasing injection rate may leads to a reduction of relative gas volume flowing through the permeability zone for microscopic sweeping of oil, lessening the oil production. The role of water in controlling the gas mobility is disturbed, weakening the WAG performance.

Indicator

WAG model without asphaltene

WAG model with asphaltene

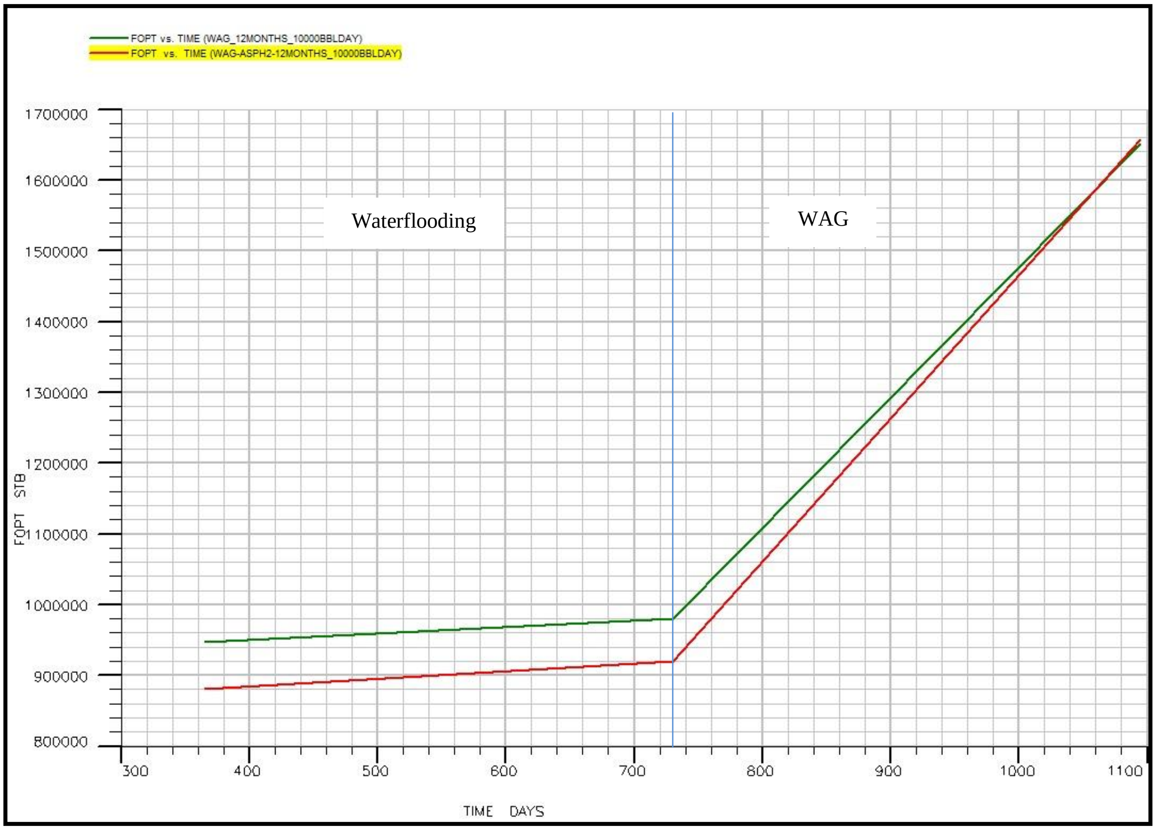

Figure 7 : Graph plotting FOPT vs. time for WAG modes with 10000 bbl/day water injection rate

Table 10 : FOPT of two WAG models with 10000 bbl/day water injection rate

Run	**Base Model**	**Field Oil Production Total (FOPT) (STB)**
1	WAG model without asphaltene	1650000
2	WAG model with asphaltene	1660000

Comparison is made between two base WAG models with water injection rate of 10000 bbl/day to observe the effect of asphaltene precipitation on oil production. Table 10 lists down the FOPT value obtained for each WAG model with 10000 bbl/day water injection rate.

A distinctive gap between two lines is clearly observed in Figure 7, showing a better oil recovery is achieved with WAG injection with no asphaltenes. Despite of there is no precipitated asphaltenes deposited on the rock surface; flow assurance problem is not encountered. Oil composition is not disturbed (Buriro *et al.*, 2013) and hence the stability state of asphaltene-resin molecule is maintained.

4.4 WAG Models with varying WAG Ratio

Indicator

WAG ratio 1:1

WAG ratio 2:1

WAG ratio 3:1

WAG ratio 1:2

WAG ratio 1:3

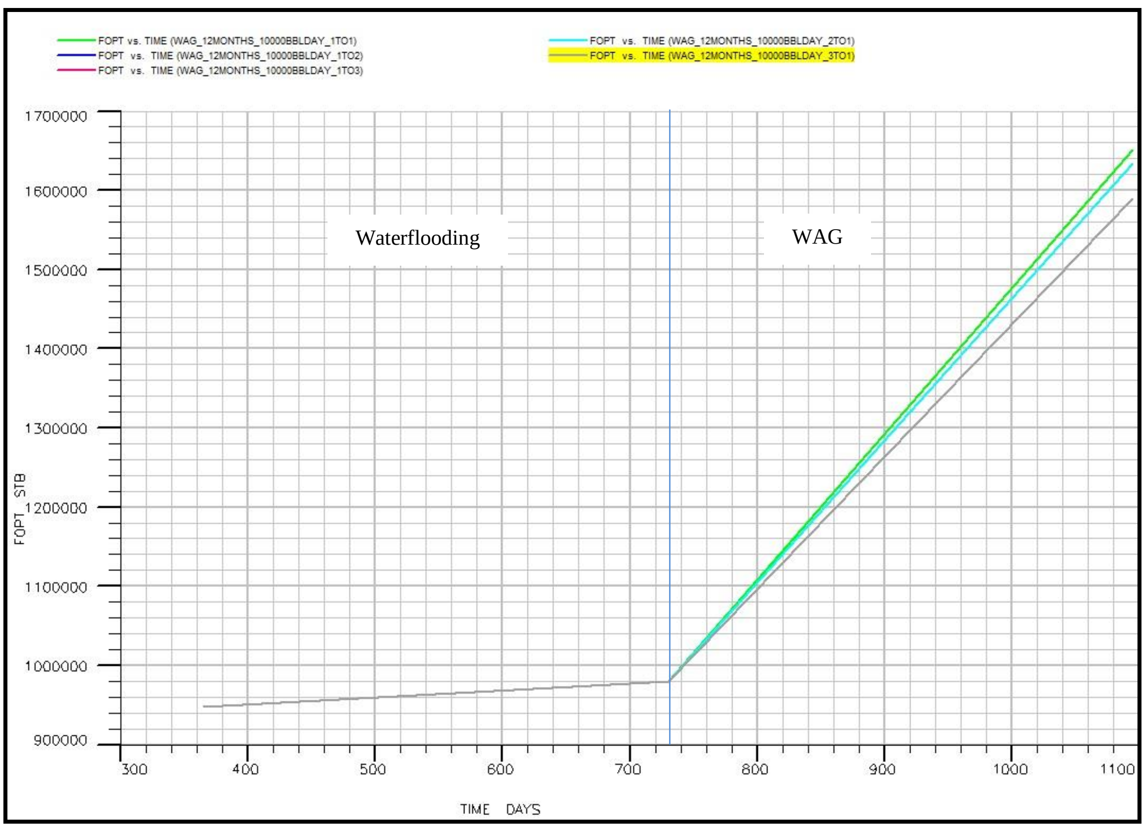

Figure 8 : Graph plotting FOPT vs. time for WAG model without asphaltene varying WAG ratios

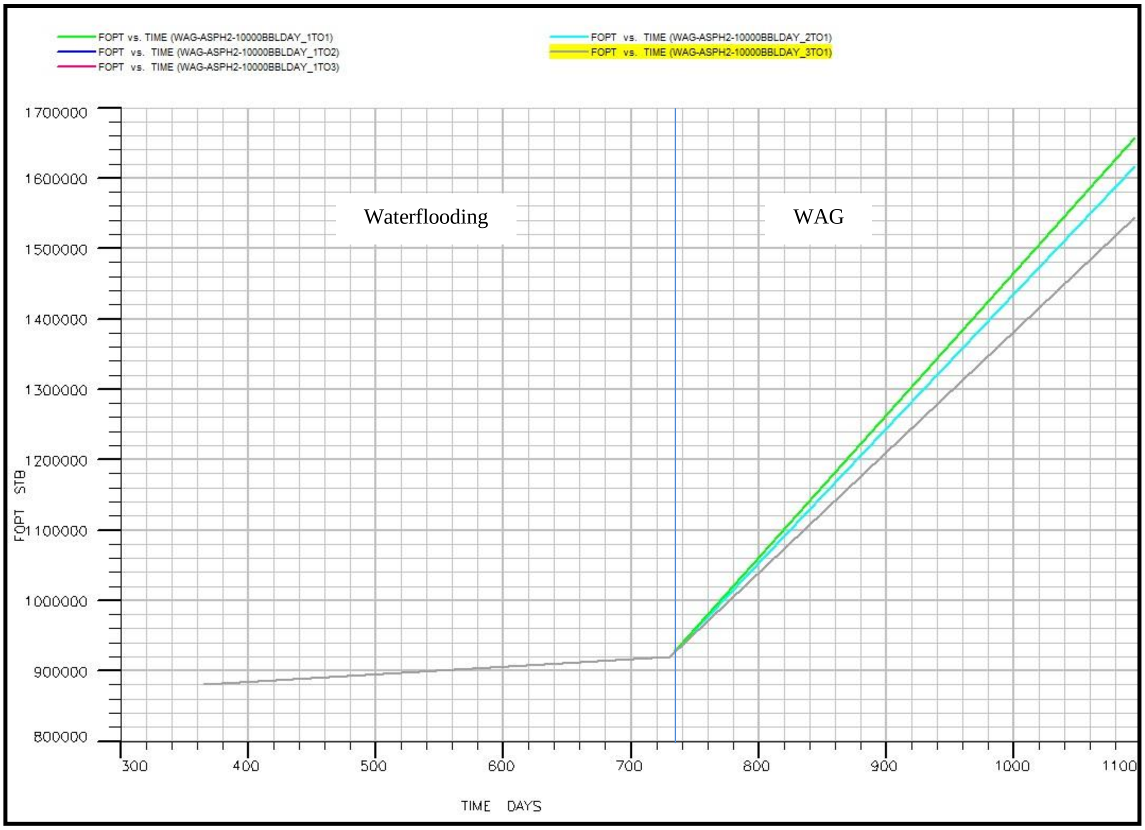

Figure 9 : Graph plotting FOPT vs. time for WAG model with asphaltene varying WAG ratios

Table 11 : FOPT of WAG models with different WAG ratios

Run	**WAG ratio**	**Field Oil Production Total (FOPT) (STB)**	
		Without Asphaltene	**With Asphaltene**
1	1:1	1650000	1660000
2	2:1	1635000	1620000
3	3:1	1590000	1540000
4	1:2	1650000	1660000
5	1:3	1650000	1660000

The second WAG parameter to be examined is WAG ratio. Five cases are proposed before the selection of optimum WAG ratio: WAG ratio of 1:1. 1:2, 1:3, 2:1 and 3:1. At a condition where 10000 bbl/day water injection rate is used on both WAG models, the outcome in FOPT is presented in Table 11.

Among all the WAG ratios attempted, WAG ratio of 1:1, 1:2 and 1:3 display a better FOPT comparing to WAG ratio of 2:1 and 3:1, see Figure 8 and 9. Increasing carbon dioxide gas volume does not further give changes in FOPT during the injection process. It might be attributed to the insolubility of carbon dioxide into brine solution in the model used.

Nonetheless, WAG ratio of 1:1 is considered to be the optimum parameter for WAG process design, since more water injection volume in WAG ratio of 2:1 and 3:1 show decreasing trend in recoverable oil. Application of WAG tapering technique occurs in such a way that more injected water is blocking the channeling of trapped oil, contributed by the insufficient contacting time of solvent and oil (Nangacovié, 2012). Instead of enhancing the oil production profile, the injection trend is more inclined to a water flooding process, opposing the advantage of water in WAG injection.

<u>Indicator</u>

WAG model without asphaltene

WAG model with asphaltene

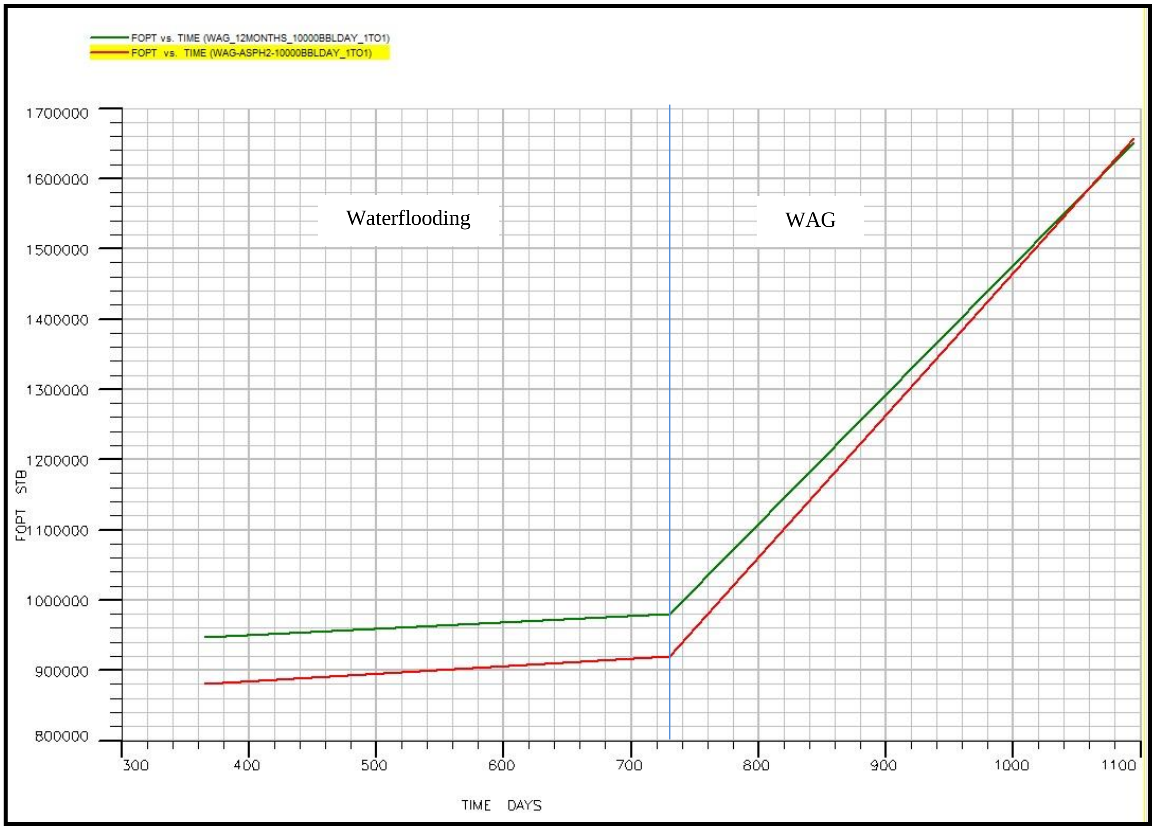

Figure 10 : Graph plotting FOPT vs. time of WAG models with WAG ratio of 1:1

Table 12 : FOPT of WAG models with WAG ratio of 1:1

Run	Base Model	Field Oil Production Total (FOPT) (STB)
1	WAG model without asphaltene	1650000
2	WAG model with asphaltene	1660000

Figure 10 shows the graph plotted in differentiating WAG model with and without asphaltene at a WAG ratio of 1:1. Table 12 stated the final FOPT of each WAG model injected with 1:1 WAG ratio. The green line (without asphaltene) lies above the red line (with asphaltene), self-explanatory on a higher recoverable oil in WAG process without asphaltenes. In mitigating the asphaltene deposited, lesser CO_2 gas should be dissolved in brine to obtain a lower concentration of gas in solution (Srivastava *et al*., 1999; Alta'ee *et al*., 2012).

4.5 WAG Models with varying WAG Cycle Time

Indicator

1 month

3 months

6 months

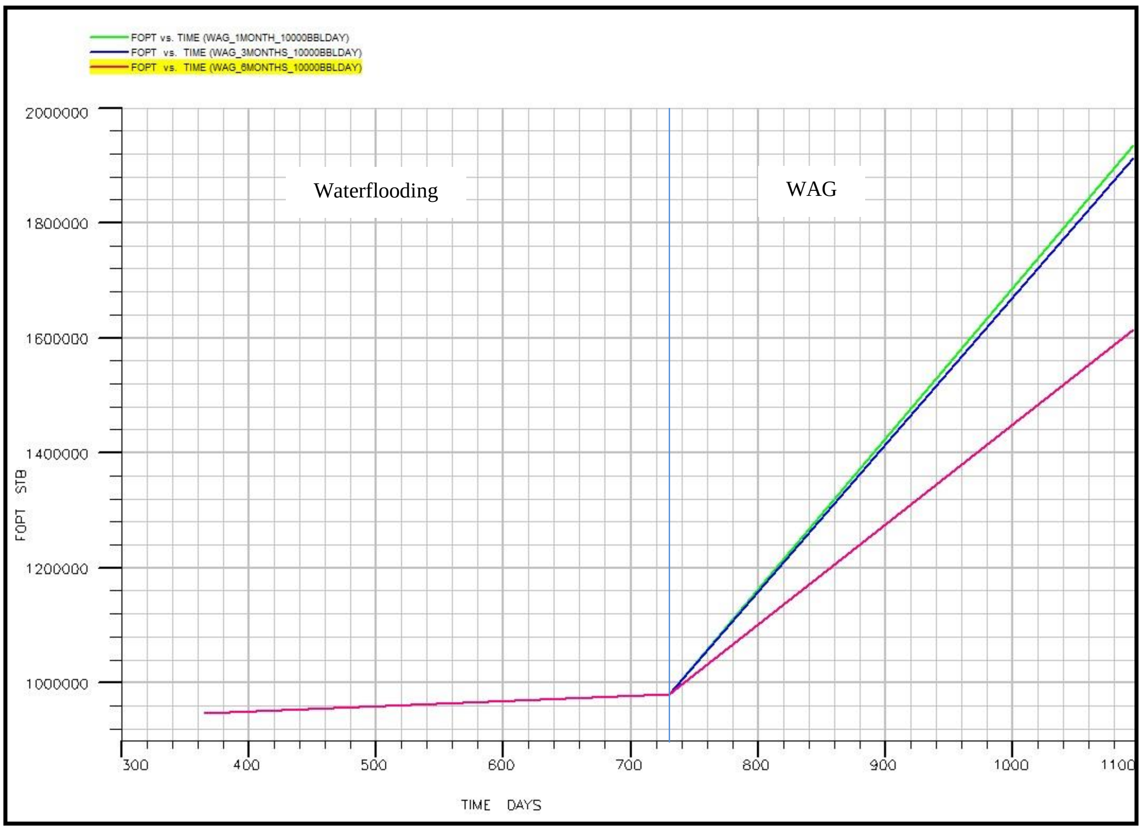

Figure 11 : Graph plotting FOPT vs. time for WAG model without asphaltene varying WAG cycle time

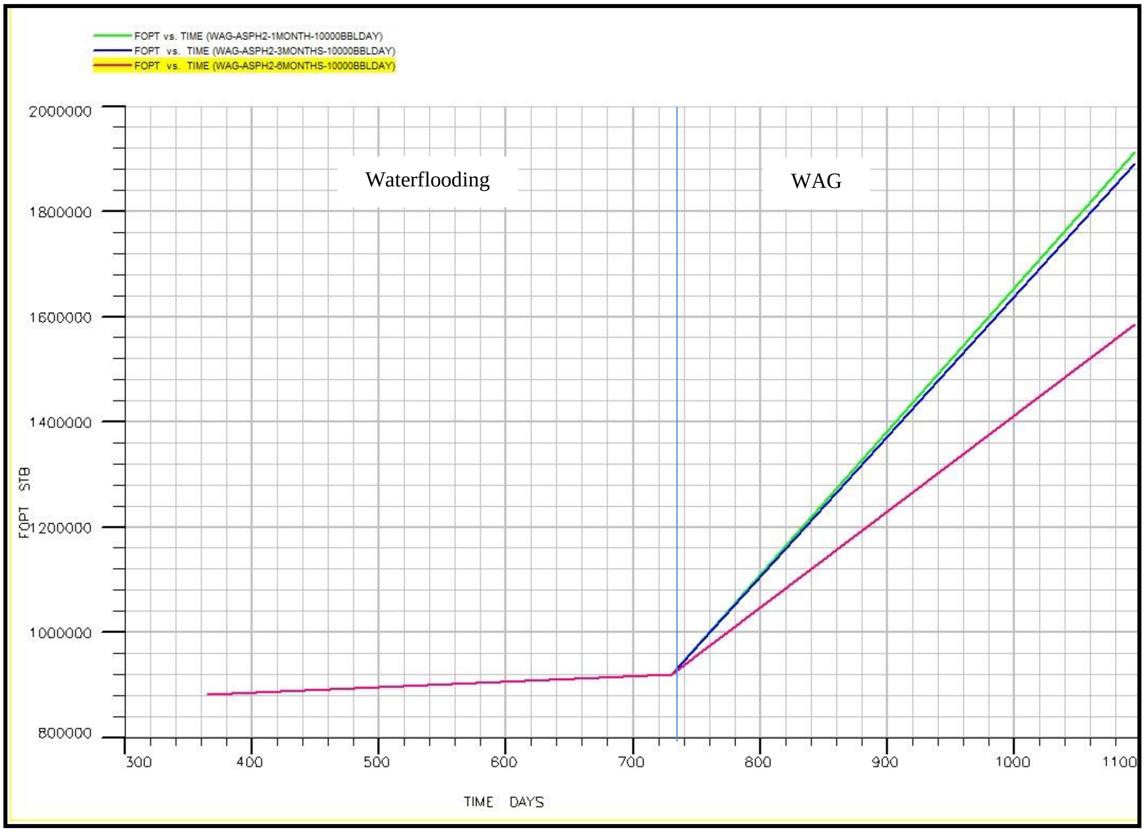

Figure 12 : Graph plotting FOPT vs. time for WAG model with asphaltene varying WAG cycle time

Table 13 : FOPT of WAG models with different WAG cycle time

Run	WAG cyclic time (month)	Field Oil Production Total (FOPT) (STB)	
		Without Asphaltene	With Asphaltene
1	1	1940000	1912000
2	3	1912000	1888000
3	6	1610000	1580000

To determine the impact of WAG cycle time on oil recovery, three cases are generated : one month WAG cycle time, three months WAG cycle time and six months WAG cycle time. In order to obtain an optimized WAG model, these three scenarios are tested in both WAG base models with two fixed parameters:

1. WAG ratio of 1:1
2. Water injection rate of 10000 bbl/day

Figure 11 shows the final recoverable oil for WAG cycle time of one month (1940000 STB) and three months (1912000 STB) are noticed with slightly higher oil production. However, a larger gap is observed on the graph plotted for six months WAG cycle time (1610000 STB), comparing to one month and three months cycle time. One month WAG cycle time achieves the best result in showing higher potential of recovering more oil. Higher frequency in switching water and gas injection improves the water macroscopic displacement efficiency of water in controlling the high mobility gas in performing microscopic displacement of oil (Kulkarni & Rao, 2005). The result obtained is similar to the work done in Nangacovié (2012) where smaller cycle time of three months gives the best FOPT value under high injection rate.

Table 13 shows a variation of FOPT value presented by different WAG cyclic time in WAG models with and without asphaltene. From Figure 12, it can be observed that similar trend in graph plotted from the simulation study on WAG cycle time. The sequence of oil production from lowest to highest is: six months WAG cycle, three months WAG cycle and one month WAG cycle.

Indicator

WAG model without asphaltene

WAG model with asphaltene

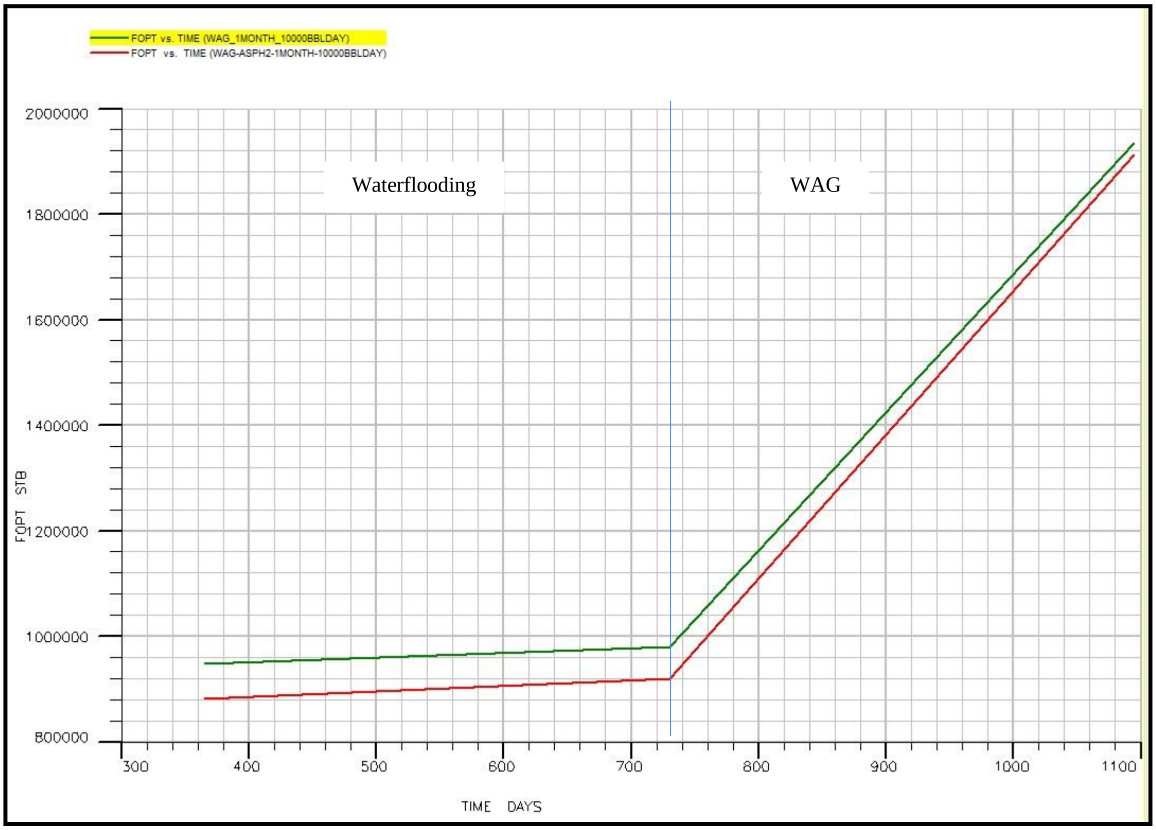

Figure 13 : Graph plotting FOPT vs. time of WAG models with WAG cycle time of 1 month

Table 14 : FOPT of WAG models with WAG cycle of 1 month

Run	Base Model	Field Oil Production Total (FOPT) (STB)
1	WAG model without asphaltene	1940000
2	WAG model with asphaltene	1912000

Oil production is WAG cycle time dependent for both WAG model with and without asphaltene. Maximum FOPT is obtained by one month WAG cycle time in WAG model without asphaltene. 1940000 STB and 1912000 STB of oil are recovered in WAG model without and with precipitated asphaltene respectively, refer on Table 14. A difference of 28000 STB is noticed (Figure 13), explains that asphaltene precipitation is an unwanted occurrence. Higher concentration of CO_2 gas injection above its critical value is proportional to the amount of aspheltene precipitated in reservoir (Chukwudeme & Hamouda, 2009).

4.5 Optimized Models: WAG Model with and without Asphaltene

Indicator

WAG optimized model without asphaltene

WAG optimized model with asphaltene

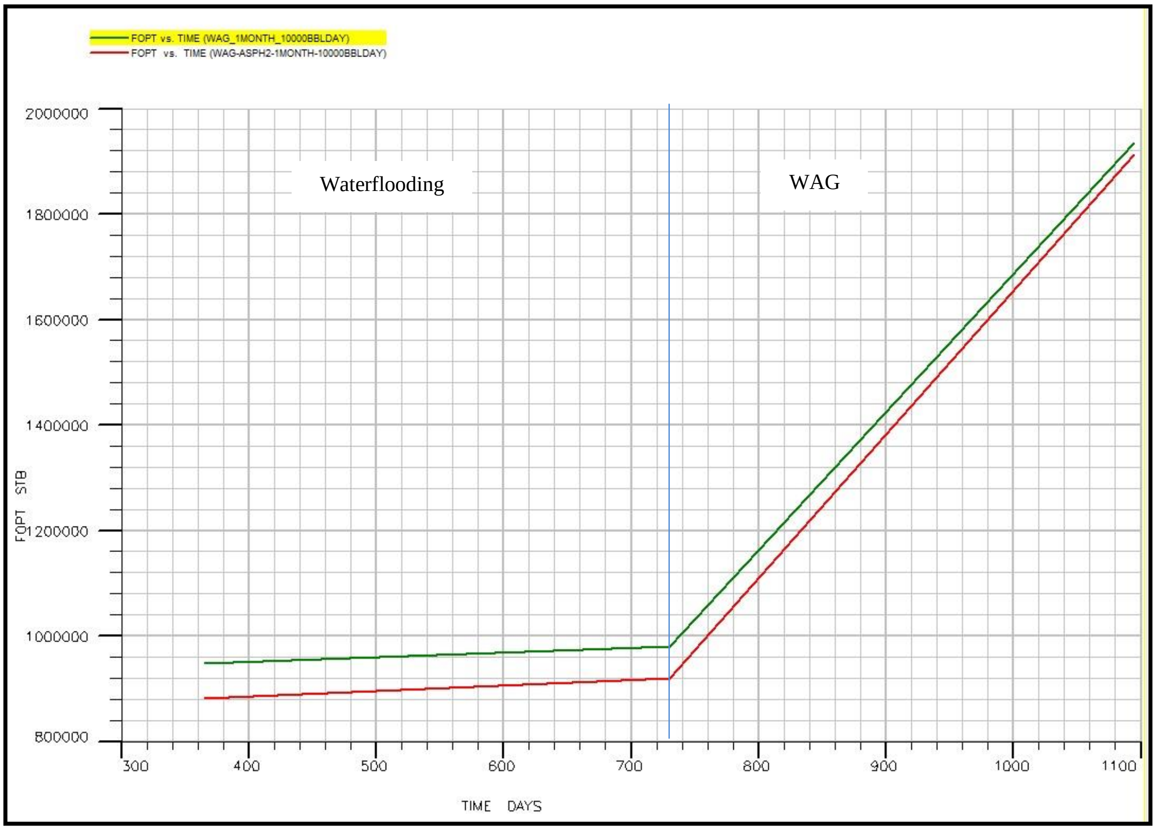

Figure 14 : Graph plotting FOPT vs. time for optimized WAG models

Table 15 : FOPT of optimized WAG models

Run	Base Model	Field Oil Production Total (FOPT) (STB)
1	WAG model without asphaltene	1940000
2	WAG model with asphaltene	1912000

Optimization of WAG process considers the best case of each WAG parameters, further enhancing the total oil production can be recovered. In this simulation study, the best cases of concerned factors are presented in Table 16.

Table 16 : Table shows best case for each WAG parameters

WAG Parameters	**Best Case**
Water injection rate	10000 bbl/day
WAG ratio	1:1
WAG cycle time	One month

Under the scenario of optimum water injection rate of 10000 bbl/day, WAG ratio of 1:1 and a more frequent WAG injection (1 month WAG cycle time) presents an optimized model in fully utilizing the flow behavior of water and gas for oil displacement process (Freistuhler *et al*., 2000; Soares, 2008). Higher microscopic displacement efficiency of gas is aided by water to trap the miscible CO_2 gas longer in sweeping the residual oil at the upswept zone in reservoir, delaying the gas breakthrough to surroundings.

From Table 15, the increment of 28000 STB in recoverable oil indicates that WAG model without asphaltene is the optimized model in this simulation study since it performs better in terms of oil production.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In short, results from the WAG models concluded that:

1. WAG injection performs better without asphaltene content, giving higher oil production.
2. Optimized WAG parameters are 10000 bbl/day water injection rate, WAG ratio of 1:1 and one month WAG cycle time in the simulation model studied.
3. Oil recovery is not always proportion to water injection rate. Relatively low injection is insufficient in promoting the macroscopic characteristic of water in oil displacement process whereas higher injection rate may be resulted in exhibiting water flooding behavior in reducing the sweeping of gas volume. Injection rate is in a function of reservoir heterogeneity.
4. WAG tapering technique of increasing water portion in a WAG ratio reduces in oil production. Lesser oil-solvent contact time is taken place whereby large volume of water blocks the pore channel of oil flow.
5. A more frequent switching of water and gas injection (shorter WAG cycle time) enhances the mechanism of WAG injection in performing the sweeping efficiency of attic and cellar trapped oil by gas and water respectively, increases the oil production.

5.2 Recommendations

Some recommendations are provided to improve this optimization study project:

- Reservoir heterogeneity of the studied simulation model can be improved by showing more variation in permeability at each grid block. Variation of permeability in each layer of the WAG models is not sufficient to exhibit the characteristic of heterogeneous reservoir.
- More parameters can be studied for WAG design optimization, such as gas injection rate and low salinity water for injection. The impact of all concerned parameters on oil recovery can then be supported with simulation study result, enables a more comprehensive study in WAG process design.
- A thoroughly screening should be performed on the constructed WAG models in examining the carbon dioxide gas solubility in brine, ensuring a good quality of simulation results obtained.
- Laboratory experiment can be conducted in comparing the results from simulation study.

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