Investigation Of Foam Stability On Injection Rate

by

Devadas S/O Vijan

14755

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum)

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
32610 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the Petroleum Engineering Programme Universiti Teknologi PETRONAS in partial fulfilment of the requirements for the Bachelor of Engineering (Hons) Degree in Petroleum Engineering

Approved by,	Approved by,
…………………………………………	…………………………………………
(DR.ALIYU ADEBAYOR SULAIMON)	(DR ABDUL HAQUE TUNIO)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2015

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

…………………………......

(DEVADAS S/O VIJAN)

ACKNOWLEDGEMENT

Firstly, I would like take this opportunity to thank all parties who have contributed and helped me in completing my Final Year Project for the past two semesters. I would like to dedicate special thanks to my project supervisor, Dr.Aliyu Adebayor Sulaimon, for his guidance and motivation throughout the completion of this project. Moreover, I would like to extend my appreciation to those who may have taught me voluntarily or involuntarily during my simulation process.

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Thank you.

ABSTRACT

The project is basically about simulation study to identify the effect of injection rate on the foam stability based on a foam model. Gas has properties of higher mobility ratio and very low density. Due to this properties, the gas tends moves upwards and override the oil zones causing less oil production. Foam flooding was introduced to avoid this gas overriding problem.

The foam model was built based on reservoir rock properties and foam half-life parameter. The analysis were done focusing on injection rate, bottom-hole pressure and decaying rate of the foam over injection time. The model was run for 19 years with injector and producer well.

The foam should be in stable condition for maximum oil recovery since foam will exhibit a behaviour where it will start to disperse when it is injected. The results are compared with the different set of parameter profiles obtained from simulation. It is found that the foam totally ruptures at a very high injection rate.

The foam ruptures as it loses it complete stability where it is mainly affected by several parameters such as mechanical entrapment, hydrogen bonding and adsorption process. The results implies that the production be optimised if the stability of the foam is maintained throughout the foam flooding.

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NOMENCLATURE

C_f	foam concentration
ρ_w, ρ_g	water and gas density
C^f_a	adsorbed foam concentration
μ_w, μ_g	water and gas viscosity
D_z	cell center depth
B_r, B_w , B_g	rock, water and gas formation volume
T	transmissibility
k_{rw}, k_{rg}	water and gas relative permeability
S_w, S_g	water and gas saturation
V	block pore volume
Q_w, Q_g	water and gas production rate respectively
P_w, P_g	water and gas pressure respectively
λ	rate decay parameter function of oil and water saturation
M_{rf}	gas mobility reduction factor
g	gravity acceleration

CHAPTER 1.0

INTRODUCTION

1.1 Background of study

Enhanced Oil Recovery (EOR) is a method used to recover the remaining trapped crude oil in reservoir. Foam flooding is one of the application being used under EOR methods. Prior to the application, gas injection was widely used in 1900's (Thomas, 2008). Gas injection was unable to exhibit a higher rate sweep efficiency to recover the hydrocarbons (Shan and Rossen, 2004). This is because gas has properties of higher mobility ratio and very low density. Due to this properties, the gas tends to move upward and override the oil zones causing less oil production. Foam injection has been introduced in oil and gas industry to solve this problem.

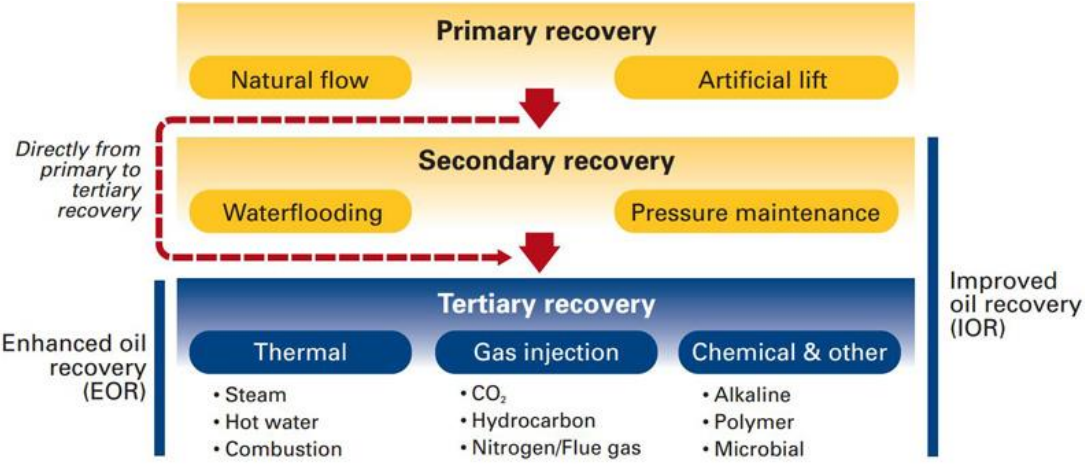

Figure 1.1: Enhanced Oil Recovery Methods *(Sevin and Capron, 2013)*

Foam is formed when two different phase solutions are mixed together. The mixture of water and gas will produce foam. The main function of foam as an EOR method is to reduce the mobility of the gas phase. Foam is more viscous compared to gas (Al-Mosaawy *et al*., 2011).

The properties of foam which are higher density and more viscous allow foam to remain in its position during injection process and prevent upward movement or flow. Foam reduces the gas mobility ratio and thus it will give a maximum sweep efficiency. For this reason, foam is better known as good blocking and controlling agent which prevent gas overriding (de Velde Harsenhorst *et al*., 2014).

Foam injection has been used as primary injection in China's Bohai Bay offshore oilfields. It was found that water injection was unable to produce the initial expected production rate which is around 32.00%. This is due to reservoir heterogeneity of the Bohai Bay and high viscosity of the oil. The production continued with the new Enhanced Oil Recovery project with foam. The displacement efficiency of oil increases 94.10 % after foam flooding replaces the water injection (Zhang *et al*., 2014).

The average recovery rate in Norwegian fields is currently 46 %. This recovery rate is expected to be increased to 50 %. There are some EOR methods were used to meet this requirement. Among the injections used in the North Sea are foam assisted WAG (FAWAG), water-alternating-gas injection (WAG), simultaneous water-and-gas injection (SWAG) injection and miscible gas injection (Awan *et al*., 2006). Foam injection is preferred in the North Sea reservoirs due to its mobility control property. In EOR the mobility control can be achieved through injection of chemicals to change displacing fluid viscosity or by decreasing specific fluid relative permeability through injection of foams.

Foam is said useful for underbalanced drilling operations. Underbalance drilling is where the wellbore pressure is less than the formation fluid pressure. Foam act as a good cuttings carrying transport agent since it has a higher viscosity compared to gas. Foam has the ability to capture and reduce the mobility of smaller particles which make the foam as a good cutting carrying agent (Srivastava, 2010).

Foam generally can support the cuttings in suspension even though drilling operations are stopped to make connections because of its density (Eren, 2004). Foam will cause a low bottom-hole pressure since it can fill the whole annulus and able to remove the cuttings at much lower annular velocities.

Although, foam is a much promising technique being used in EOR, it still has a drawback. A major concern with the application of foam in enhanced oil recovery (EOR) method is the stability of foam. The stability of the foam is measured by the time taken for the foam to collapse. The foam must remain stable for a successful optimum recovering of crude oil from the reservoir.

1.2 Problem statement

Foam is a mixture of aqueous and non-aqueous solution. Foam will exhibit a property where it will start to disperse as it start to propagate due to the foam stability reduces.

The stability of foam is much affected by the injection rate being applied on the foam. The injection rate applied in the well directly affects the bottom hole pressure. This statement can be proven by the productivity index equation.

$$PI = \frac{Q_o}{P_r - P_{wf}} = \frac{0.00708\, k\, h}{\mu\, B_o\ (\ln r_e / r_w)} \tag{1.1}$$

where,

PI = Productivity Index, stb/d/psia

Q_o = Flow rate, stb/d

P_r = Reservoir Pressure, psia

P_{wf} = Well Flow Pressure, psia

k = Permeability, md

h = Height, ft

u = Viscosity, cp

B_o = Formation Volume Factor, bbl/stb

r_e = Drainage radius, ft

r_w = Wellbore radius, ft

The above equation is used to predict the inflow performance of the well. Higher PI shows a better inflow performance. Simplifying the above equation by making the other parameters constant will give the following equation.

$$Q_o = PI\left(P_r - P_{wf}\right) \quad where \quad \left(P_r - P_{wf}\right) = (\Delta P)$$

$$Q_o = PI\ (\Delta P) \tag{1.2}$$

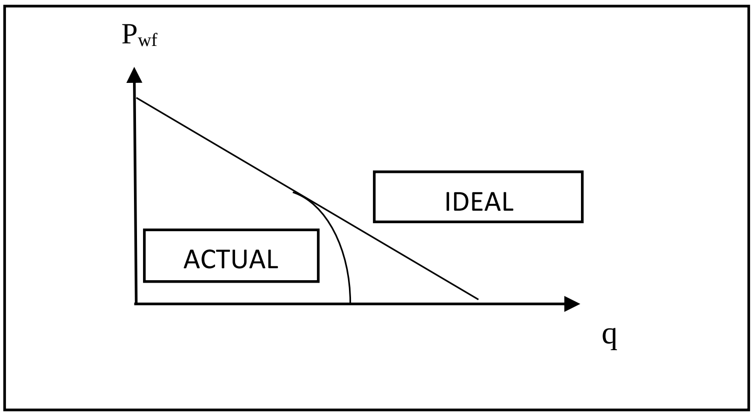

Figure 1.2: Pressure vs rate profile

The graph implies that when the pressure is plotted against rate it supposed to produce a straight line. The straight line implies an ideal reservoir pressure where in most cases it does not occur. The actual graph will be the curve line where the line will intersect the X-axis giving the maximum flow rate (absolute open flow-AOF) of the well could theoretically deliver with zero pressure.

Foam exist as more than one component where it is made of gas and water. Thus, when foam is injected the pressure distribution across the reservoir will not be uniform. The pressure will shows a fluctuation in the reading as the injection rate changes from lower to higher and vice versa. This happen because the as the foam is being injected the foam starts to decay over time and eventually destabilise. The foam will exhibit a behaviour where it will start to disperse when it is injected due to liquid drainage from Plateau borders (lamellae intersections) and lamellae and to capillary suction. This prompts to burst of the foam films and eventually makes the foam to be unstable.

1.3 Objectives

The objectives that need to be achieved when completing this project are:

a) To model foam propagation and pressure distribution during foam flooding operation
b) To evaluate the foam decaying rate at various rate of injection parameters.
c) To investigate factors that affects foam stability

1.4 Scope of study

The scope of study for this project is mainly concerns about the injection rate parameter. This project is mainly about simulation work and does not involve any experimental work. Nevertheless, literature studies were done for both simulation and experimental work to get a better understanding about foam. The findings obtained from the literature studies were utilised to identify what are the parameters that can be manipulated in simulation.

The simulation work involves parameters such as injection rate, pressure and production rate. These parameters are very important as the pressure and production rate will be directly affected by changing the injection rate. Some of the parameters such as bubble size of foam is ignored since experimental work is required. The foam stability will be analysed in terms of foam decaying rate and adsorption factor. Basically, the simulation work will be carried out until the maximum injection rate where the foam loses its stability.

1.5 Relevancy of study

The project will focus on the scheme of foam injection, foam stability and the effect of injection rate on foam. This project will significantly contribute to the development of Enhanced Oil Recovery sector in Malaysian petroleum industry. The result produced by end of this project will be used to manipulate and increase the usage of foam in EOR for optimum hydrocarbon recovery.

1.6 Feasibility of study

This project is mainly divided into two stages; the first stage will be complete literature studies about the project and the second stage will be producing data and result. The project activities are feasible to be carried out within two semesters. The literature review and methodology of the project was prepared from September 2014 until December 2014. While, the results and discussion is being prepared from May 2015 until August 2015 after the simulation work has been carried out. This time period was sufficient enough to carry out all the planned activities for this project.

CHAPTER 2.0

LITERATURE REVIEW

2.1 Application of foam

Foam is formed when gas bubbles are spread uniformly throughout a continual liquid part. Foam properties depends on fluid, rock and different reservoir parameters (Alvarez & Han, 2013). Studies revealed that foam could be a uniform fluid and only known compressible non-Newtonian fluid (Eren, 2004).

The characteristics of foam which has higher viscosity and lower density makes it more preferable method than gas injection in Enhanced Oil Recovery. However, foam will exhibit a behaviour where it will start to disperse when it is injected due to liquid drainage from Plateau borders (lamellae intersections) and lamellae and to capillary suction. The liquid drainage is aided by the capillary pressure. The liquid will gradually drain out of the foam with the increase of time.

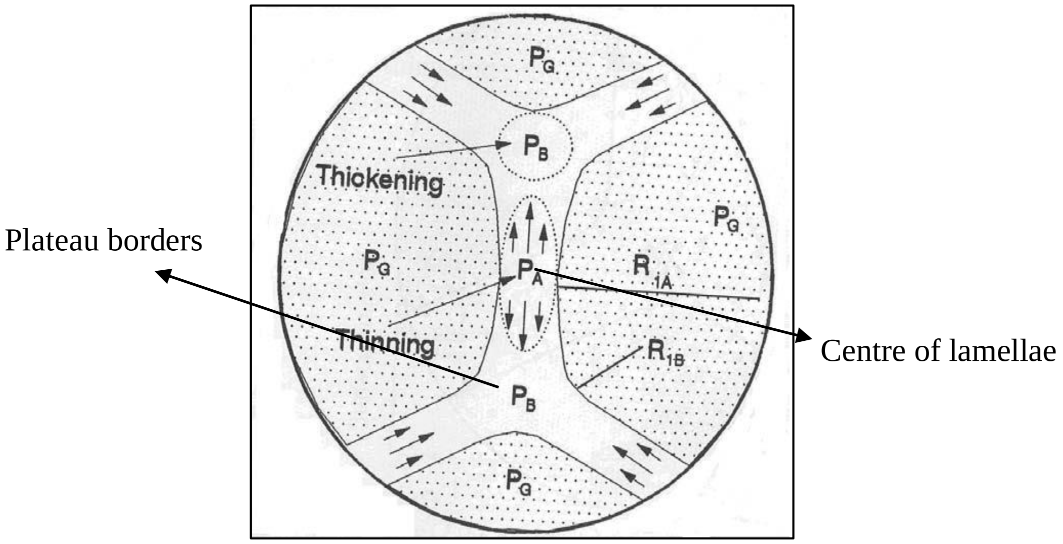

Figure 2.1: Foam lamellae *(Srivastava, 2010)*

The radius of curvature at the centre of the lamella is much larger than the radius of curvature of Plateau borders. The gas phase will be same throughout the foam lamellae but the liquid phase pressure will be change due to the capillary force. The liquid pressure inside the centre of lamellae will be much higher compared to the Plateau borders. This pressure gradient difference will cause the movement of liquid from higher pressure to lower pressure. So, the liquid will start to flow from the centre of lamellae to Plateau borders.

As the liquid continues to flow, this prompts to the burst of the foam films (Salem et al., 2013). Eventually the foam will decay and separates into liquid (aqueous) and gaseous (non-aqueous) state (Teerakijpaiboon & Srisuriyachai, 2013). The foam volume will disintegrate once production of the foam is stopped. This conditions lead to the statement that foam is not a stable fluid.

The condition of foam depends on the amount of liquid present. The foam structure will be seen as solid formed during dry foam whereas during wet foam the structure is spherical bubbles. Foam can be divided into foam in porous media and bulk foam. Foam decreases gas mobility and trap a fraction of flowing gas. This will leads to increase of gas saturation in porous medium. The liquid relative permeability is decreased as a result of increased gas saturation. The reduction in relative permeability lowers the mobility of displacing fluids and thus improves displacement efficiency of the process (Srivastava, 2010).

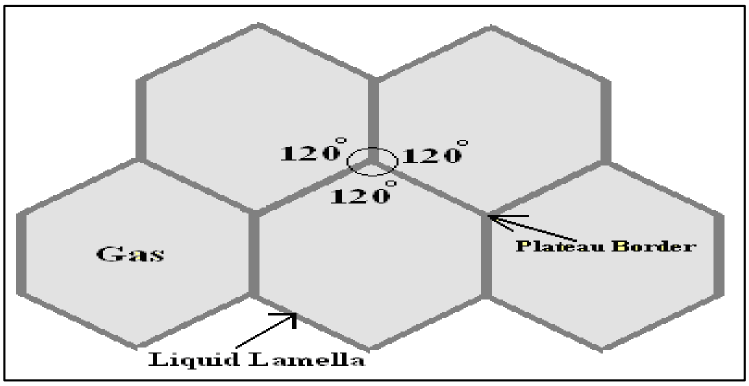

Figure 2.2: Foam system *(Al-Mosaawy et al., 2011)*

2.2 Half-life of foam

Foam stability is defined in terms of its half-life which is the time required for half of the foam volume to drain out is called half-life of foam (Van der Bent, 2014; Issham *et al.*, 2013). The half-life of foam implies that foam effectiveness will typically reduce over time, even in conditions very favourable to foam stability. The half-life of foam occurs when there is a gravity drainage. The reduction in foam effectiveness over time is represented by foam decay. Foams are divided by thin layers. Liquid gravity will cause the liquid in the liquid layer to drain out. The half-life of foam is normally used to evaluate the concentration of stabilising agent or surfactants needed to be added with the foam to achieve stability (Teerakijpaiboon & Srisuriyachai, 2013).

The half-life of the decay can be a function of either oil or water saturation. The presence of both water and oil will induce the reduction in effectiveness of foam stability .On other hand, the foam will decay with the minimum half-life when the decay half-life is a function of both water and oil saturation. The function of decay rate with water saturation and oil saturation can be defined as λ (S_w , S_o). This relation will be later used in the foam conservation equation.

Foam is normally transported as a function of water or gas. Therefore, the foam distribution is explained in the below conservation foam equation. The equation implies that foam distribution is actually a function of several parameters such as concentration, viscosity, formation volume factor, water and gas saturation, porosity, permeability and decay rate.

$$\frac{d}{dt}\left(\frac{V\,S_g\,C_f}{B_r\,B_g}\right)+\frac{d}{dt}\left(V\,\rho_r\,C_f^n\,\frac{1-\Phi}{\Phi}\right)$$

$$=\sum\left[\frac{T\,k_{rg}}{B_g\,\mu_g}M_{rf}\left(\delta P_g-\rho_g\,g\,D_z\right)\right]C_f+Q_g\,C_f-\lambda\left(S_w,S_o\right)V\,C_f \qquad (2.1)$$

Referring to the above foam conservation equation of gas and water, the mobility reduction factor, (M_{rf}) serves as an important parameter in differentiating the two equations. The mobility reduction factor only present in the conservation equation of function of gas.

2.3 Injection rate

The reservoir characteristics will determine the rate of injection need to be applied for EOR method (Hou *et al*., 2013). The different injection rate of foam will produce various set of production profile (Genetti *et al*., 2003). Injection rate will significantly affect the cumulative production time (Zhao *et al*., 2013; Yang., 2007). Higher injection rate may lead to the disintegration of the foam. The lower injection rate will gives lower cumulative production time. The higher and lower of injection rate will be applied at different contacts (oil-water contact or gas-oil contact) to optimise the production rate.

When foam is injected in the reservoir it will first goes into higher permeability areas (Element *et al*., 2013). However, flow resistance increases when foam enters this areas. Therefore foam starts to enter the low permeability zones which are usually have low sweep efficiency. The contacts region have different set of permeability values throughout the reservoir. The injection rate has to take account the permeability distribution so the reservoir production can be optimised in an effective manner (Ahmadloo *et al*., 2009).

The injection rate has a great effect on the pressure. The average reservoir pressure near the injectors will increases as the injection rate decreases. At the same time the pressure near the production wells will decrease. This statement is proven by the Peaceman’s Well Index model which was introduced back in 1970’s (Shu, 2005). This Peaceman’s model is considered as first theoretical study of well equations. Peaceman‘s model give a clear picture on flowing bottom hole pressure.

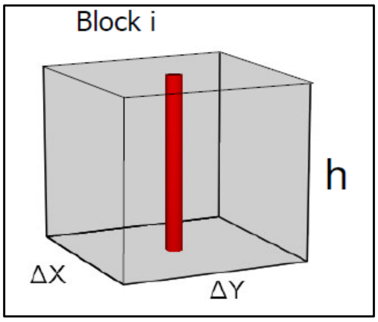

Figure 2.3: Peaceman's model *(Shu, 2005)*

$$Q = \frac{2\,\pi\,k\,h\,(p_o - p_w)}{\mu\,\ln(r_e - r_w)} \tag{2.2}$$

where,

Q = Flow rate, stb/d

k = Permeability, md

h = Height, ft

P_o = Reservoir Pressure, psia

P_w = Well Flow Pressure, psia

u = Viscosity, cp

r_e = Drainage radius, ft

r_w = Wellbore radius, ft

The main assumptions of this model are:

I. Single isolated well,
II. Fully penetrating the grid block,
III. Single-phase radial flow and
IV. No interaction with boundaries or other wells.

The Peaceman's model is related by the given equation. At high injection rates the viscous forces driving the fluids through the reservoir will prevail over the component of the gravity force resulting in the unstable displacement especially when foam is being injected. Higher injection rate can cause a larger disparity between production and injection well. Injection rate must be controlled to prevent the foam from flowing out of target zones or out of pattern .The injection rate should not more than the fracture gradient (Salem *et al*., 2013 ; Wassamuth *et al*., 2005).

2.4 Flow of foam in porous medium

The presence of foam will greatly have an effect on the flow mechanisms of liquid and gas in porous medium (Farajadeh *et al*., 2012). Liquid and gas follows totally different path once each flow accordantly through a porous medium. An important factor of foam injection in the reservoir will be adsorption and mechanical trapping. Adsorption refers to the interaction between solid surface and foam molecules.

The foam adsorption is a process where the liquid or gas accumulate on a surface (rock) forming a particle. In this scenario, the surface is known as adsorbent while the particle formed is known as the adsorbate. The adsorption process is different from absorption, where a substance dissolve into a liquid or solid to form a solution (Van Der Bent, 2014). This process is mainly aid by the physical adsorption properties of the foam and hydrogen bonding. Foam mechanical entrapment occurs when foam molecules become stuck in narrow flow channels. The level of foam retained in a reservoir rock depends on permeability of the rock, rock heterogeneity (carbonate & sandstone) and foam concentration (Yuan and Pope, 2012). Below is the equation which shows the correlations of parameters which affects the foam adsorption.

$$\text{ŗ} = \mathrm{V}.\left[\frac{(\,1-\,\Phi)}{\Phi}\right] p_r\, C_f \tag{2.3}$$

where ,

V = Pore Volume

Φ = Porosity

ρ_r = Density of Rock

C_f = Foam concentration

2.5 Foam parameters

The characteristics of foam depends on several parameter such as texture, bubble size and quality. These parameters determine the behaviour of the foam when it is injected in wells.

2.5.1 Foam texture

The texture of foam is described by the distribution and size of the bubble size. Foam texture determines the mobility of foam phase. Fine foam with smaller bubble will have smaller diameter compare to pore diameter. So, the foam flows as dispersed bubbles in the pore channels. Bulk foam with a broad gas-bubble size distribution will be less stable. This is because of gas diffusion from small to large gas bubbles. Coarse foam will have larger diameter than the pore diameter. The foam will flows as progression of films that separate individual gas bubbles. Course foam has large and polyhedral bubble shape whereas fine foam has smaller and spherical bubbles (Van Der Bent, 2014). This explains how foam propagates through a permeable medium.

2.5.2 Foam quality

Foam quality is the volume fraction of the foam which contains gas or the gas volume fraction of the total injected fluid rate. The foam quality is affected by the pressure and temperature because the gas volume can changes due and gas compressibility and thermal gas expansion The gas can either dissolve in the liquid phase or can come out of solution (Holtz *et al.*, 2008; Honarpour *et al.*,2010 ; Kam *et al.*, 2003; Kam, 2008). The foam quality equation is shown as below.

$$Foam\ quality = \frac{gas\ volume}{gas\ volume + liquid\ volume} \times 100 \tag{2.4}$$

The foam quality has a greater effect on the foam viscosity. According to Peaceman's model equation the viscosity is inversely proportional to the injection rate. When the amount of gas present in the foam is high it will cause in the increase of foam viscosity (Sharma *et al*., 2011). The injection rate should be higher to make the high viscosity foam to propagate (McMillan, 2008). Since the concentration of gas is higher compare to the amount of liquid present in the foam, the gas will start to disperse after it reach the optimum point. Beyond this point, the foam viscosity will drastically drop.

CHAPTER 3.0

METHODOLOGY

3.1 Research methodology

This project is carried out based on researchers published journals and technical papers. The papers are carefully studied and reviewed to gather general understanding on this project. The study of the journal papers is done to come up with a proven method to carry out this project successfully.

3.2 Simulation in ECLIPSE

For this project, ECLIPSE Simulator 100 & 300 will be used since this software is compatible of producing data for foam. The ECLIPSE E100 has an integrated black oil simulator and ECLIPSE E300 is specialized in compositional modelling. The ECLIPSE E300 can use various calculation methods for the next time step; fully implicit, adaptive implicit and "implicit pressure explicit saturation” or IMPES. The fully implicit method provides the best stability for long time steps, while the adaptive implicit method tries to save computation time and memory by making cells implicit only when necessary. ECLIPSE is an oil and gas simulator originally developed by ECL (Exploration Consultants Limited), a division of Schlumberger. The name ECLIPSE originally was an acronym for “ECL’s Implicit Program for Simulation Engineering”. ECLIPSE uses the finite volume method to solve material and energy balance equation modelling a subsurface petroleum reservoir (Boeije *et al.*, 2013). It allows direct simulation of foam propagation and other effects such as decay rate which can be observed in detailed like in laboratory experiments. This approach provides the future expected result in numerical way and thus leading to identify methods to optimise production rate (Fayers *et al.*, 2000 ; Gai 2004).

3.3 Base case preparation

This project requires simulation work to produce results. For the simulation to be run base case are required. The result will be produced based on the base case values. The summary of simulation process which will be carried out for this project is shown as in the workflow chart below.

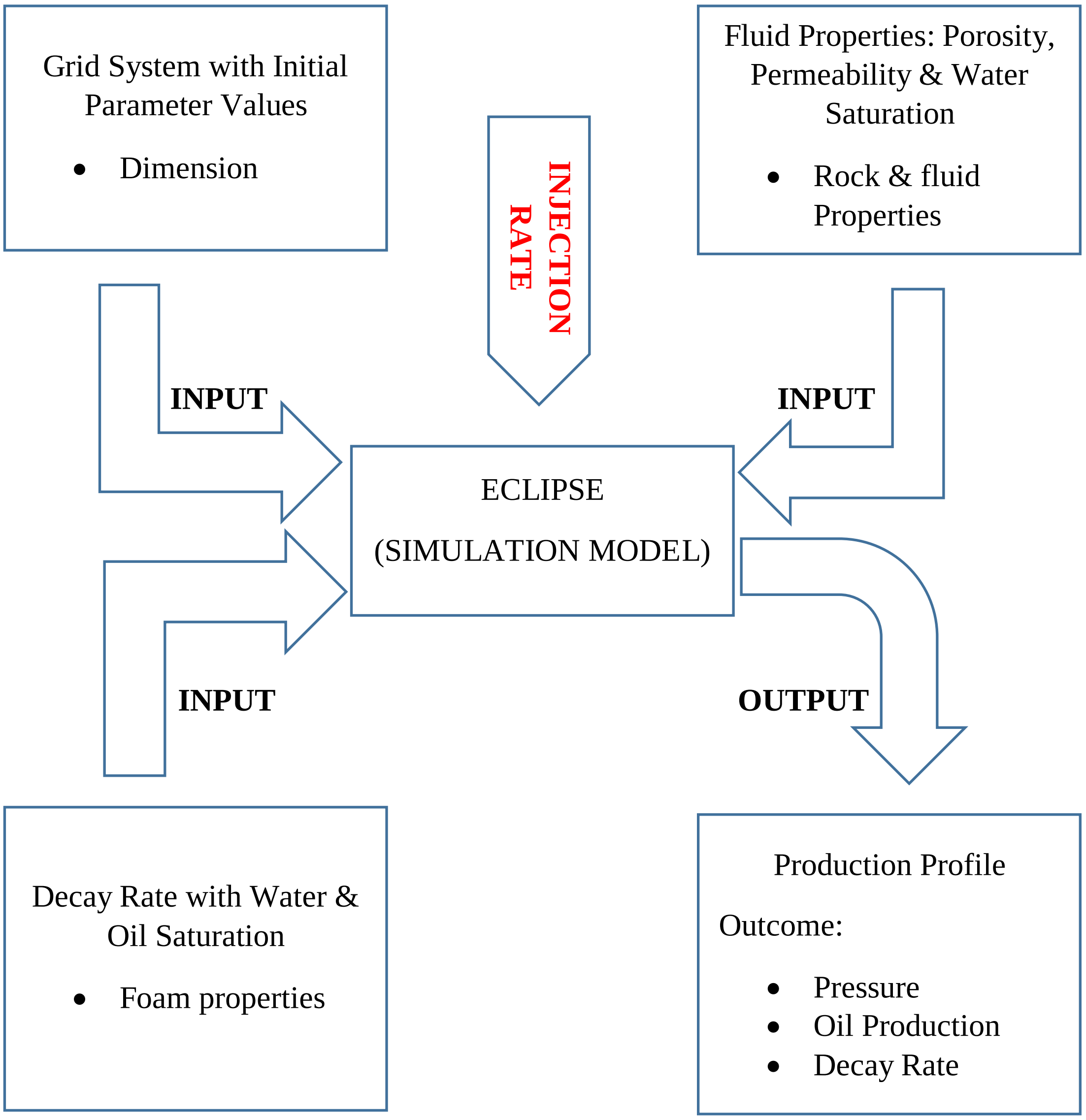

Figure 3.1: Summary of ECLIPSE simulator work

3.4 Foam model

The foam model used in this project consists of 10×10×3 grids blocks. Each grid block resulting in a rectangular reservoir. This foam model basically has three layers. An injection well and a production well is placed in the foam model. The production well is set to be at 10 10 3 while the injection well is set to be at 1 1 1. The density of water is set to 64.79 lbm/ft^3 , oil is set to 49.1 lbm/ft^3 and gas is set to 0.06054 lbm/ft^3. This foam model will be run in the simulation with a lifespan of 19 years. In all simulations the injection rate and bottom- hole pressure is fixed at the production well. The bottom-hole pressure at the production well is fixed 1000 psia for all the simulations. The simulations start with the initial injection rate of 1000 stb/d. The injection rate is increased until it reaches 8000 stb/day. After all the parameter values are set, the simulation is run in ECLIPSE launcher.

The results obtained were analysed in the form of decaying rate, production rate and pressure distribution between the injection well and the production well. The injection well is later set at the different coordinates to see the production rate and pressure distribution. When the injection well is being set at different locations, all the initial foam model parameters are remained as constant. Only the injection rate parameter was altered to obtain different set of result. Different injection scenarios were carried out to view the outcomes in terms of the production rate. The results obtained were plotted in the graphical method and also shown as 3D view.

3.5 Project Activities

In this project, different injection simulations were carried out to analyse the foam stability under varying injection rate. All the injection simulations were carried out with the initial parameters such as density and oil saturation being kept as constant.

The injection scenarios carried out are as follows
Simulation 1: Base Case: Foam flooding with initial (constant) parameters
Simulation 2: Simulation model with different parameters of foam flooding
Simulation 3: Foam flooding with stabilising agent
Simulation 4: Comparison between simulation results

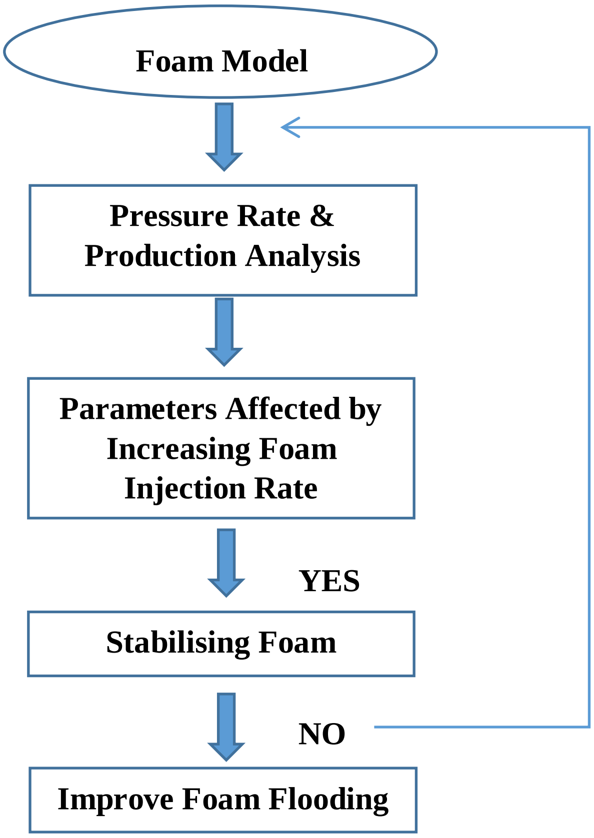

Figure 3.2: Flowchart on Foam Injection Using ECLIPSE Simulator

3.6 Key Project Milestones

There are several key milestones that need to be achieved by end of the Final Year Project 2 (FYP 2) which will in the time period of May 2015 to August 2015. Each key milestones are very important so the project can be proceeded to the next stages. Below is the key milestones for this project:

Table 3.1: Key Milestones for FYP 2

NO	**KEY MILESONES**	**MAY**	**JUNE**	**JULY**	**AUGUST**
1	Create Foam Model	🟥			
2	Analyse Pressure and Production Rate		🟥		
3	Detailed Result Analysis		🟥	🟥	
4	Progress Report Submission and Poster Presentation			🟥	
5	Viva & Submission of Hardbound Final Report				🟥

The details of the activities which will be carried out throughout FYP 2 is shown in the form of Gantt chart in the next part.

3.7 Project Timeline (Gantt Chart)

FYP 1															
NO	**DETAIL/WEEK**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	**Choosing Project Title & Supervisor Consultation**	🟩	🟩												
2	**Preliminary Research Work**		🟩	🟩	🟩										
3	**Preparation & Submission of Extended Proposal**					🟩	🟥								
4	**Approval of Extended Proposal**							🟩							
5	**Preparation for Proposal Defence**								🟩	🟩					
6	**Further Work on Literature Review**										🟩	🟩			
7	**Software Approach of Eclipse Simulator**											🟩			
8	**Sample Data Gathering To Be Run in Software**											🟩			
9	**Preparation & Submission of Interim Report Draft**											🟩	🟩		
10	**Approval of Interim Report Draft**													🟥	
11	**Interim Report Submission**														🟥

Figure 3.3: Gantt Chart for FYP 1

🟩 **PROCESS** 🟥 **SUGGESTED MILESTONE**

FYP 2															
NO	**DETAIL/WEEK**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	**Preliminary Research Work Continues**	🟩	🟩	🟩	🟩										
2	**Simulation work begins with the foam modelling**		🟩	🟩	🟩	🟩	🟩								
3	**Submission of Progress Report**							🟥							
4	**Simulation work continues**							🟩	🟩	🟩					
5	**Pre-Sedex Poster Presentation**										🟥				
6	**Project improvement under examiner suggestion**										🟩	🟩			
7	**Project work continues with a solution identification to stabilise foam**											🟩	🟩		
8	**Submission of Technical Paper**													🟥	
9	**Submission of Final Draft**													🟥	
10	**Viva / Oral Presentation**														🟥
11	**Submission of Hardbound Final Report**														🟥

Figure 3.4: Gantt Chart for FYP 2

🟩 **PROCESS** 🟥 **SUGGESTED MILESTONE**

CHAPTER 4.0

RESULTS AND DISCUSSIONS

The base case is run on the foam model with initial injection rate of 1000 stb/d and bottom hole pressure 1000 psia. The initial run is injected with foam with no further modification for 19 years (2015-2034). Figure 4.1 and 4.2 show the oil saturation and pressure distribution at initial condition of foam flooding.

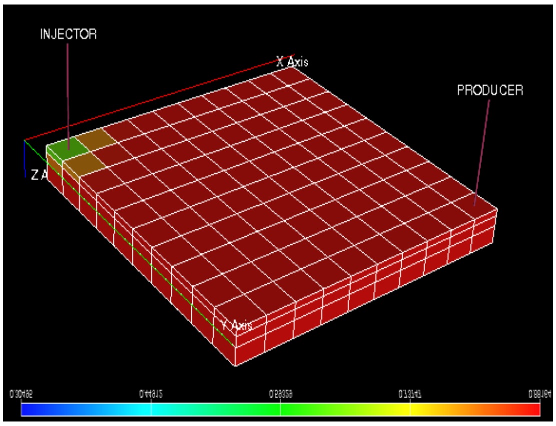

Figure 4.1: Oil saturation at initial rate

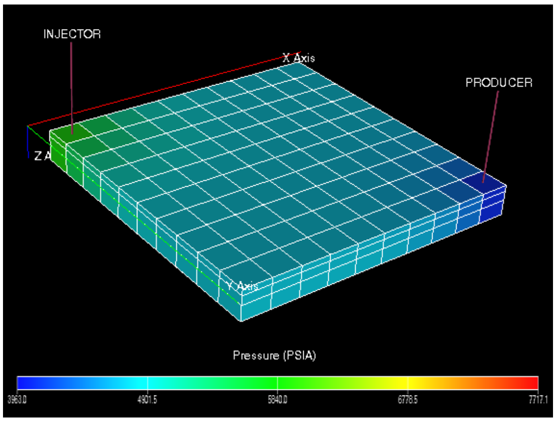

Figure 4.2: Pressure at initial rate

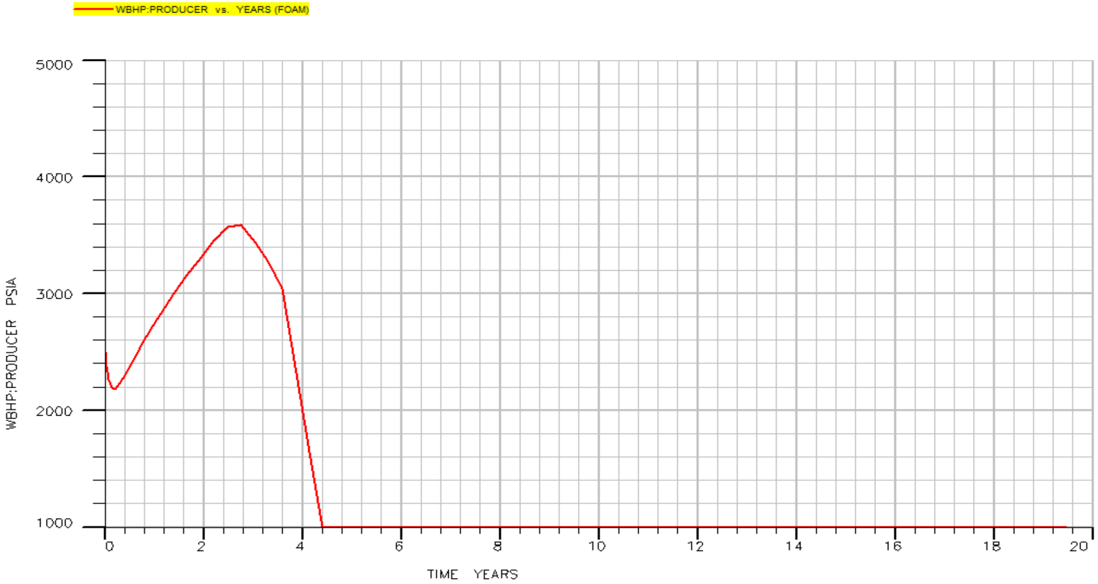

Figure 4 .3: Bottom hole pressure at initial rate of 1000 stb/d

The pressure at initial rate of 1000 stb/d will be around 2500 psi. The pressure at this rate will be optimum at the 2.4 -2.8 years. After 2.8 years, it seems that pressure begins to .drop and from 4.2 years onwards the pressure becomes constant. The pressure at the initial stage is sufficient enough to initiate the foam propagation at the 4.1 years.

The simulation continues with the increasing of injection rate by 1000. It is observed that the pressure distribution changes when the injection rate increases. The pressure curve for each injection rate shows continues fluctuation. This condition applies to all the three layers with the same trend but with different pressure values.

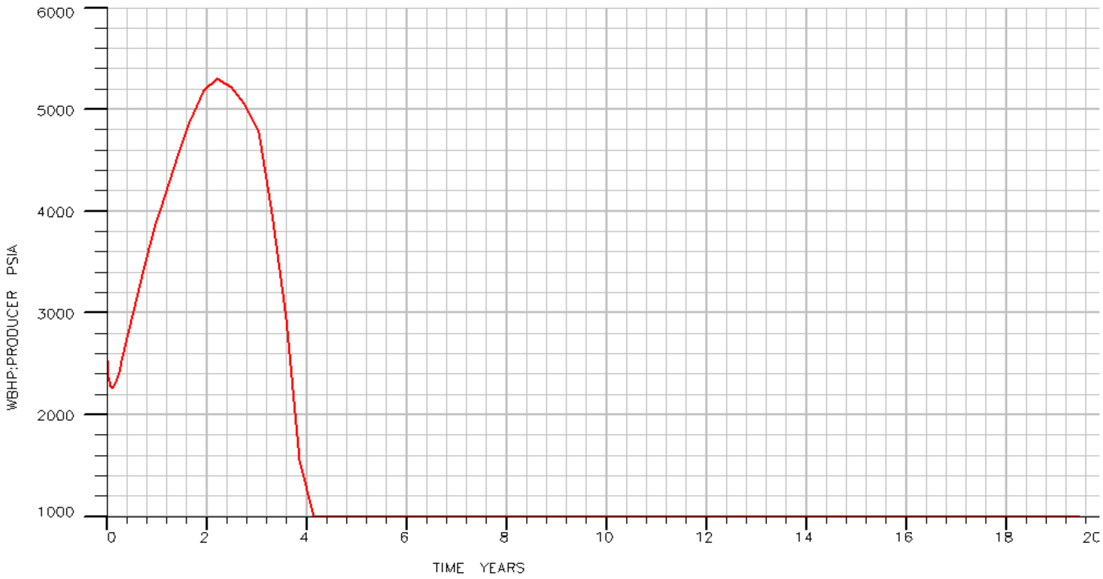

Figure 4.4: Bottom hole pressure at 2000 stb/d

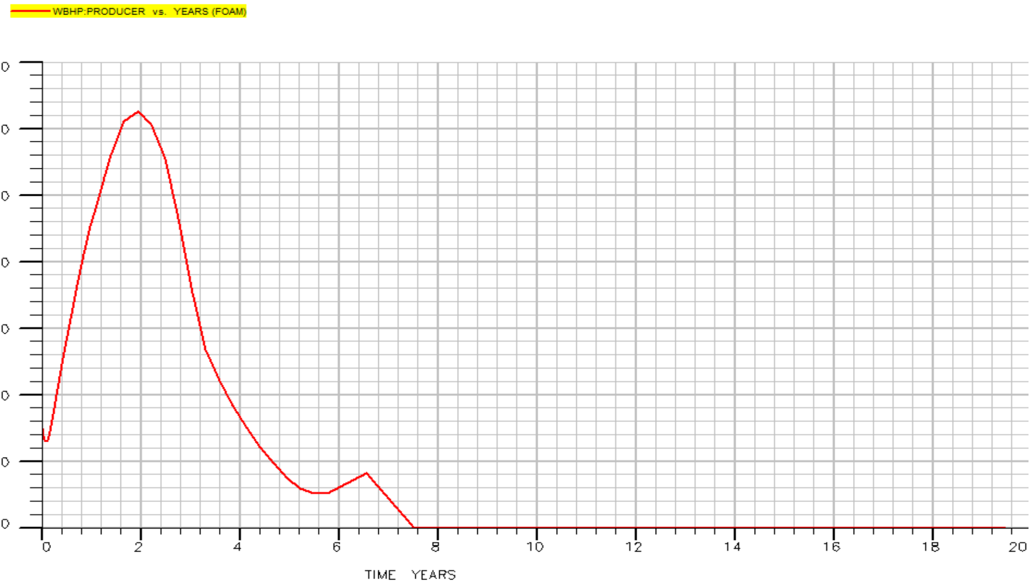

Figure 4.5: Bottom hole pressure at 4000 stb/d

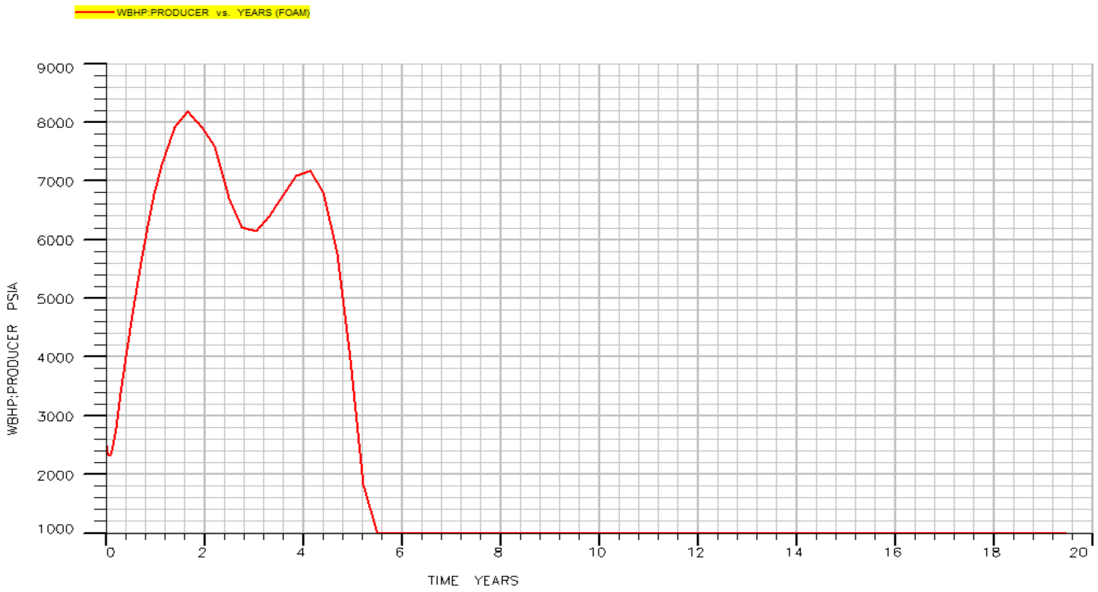

Figure 4.6: Bottom hole pressure at 6000 stb/d

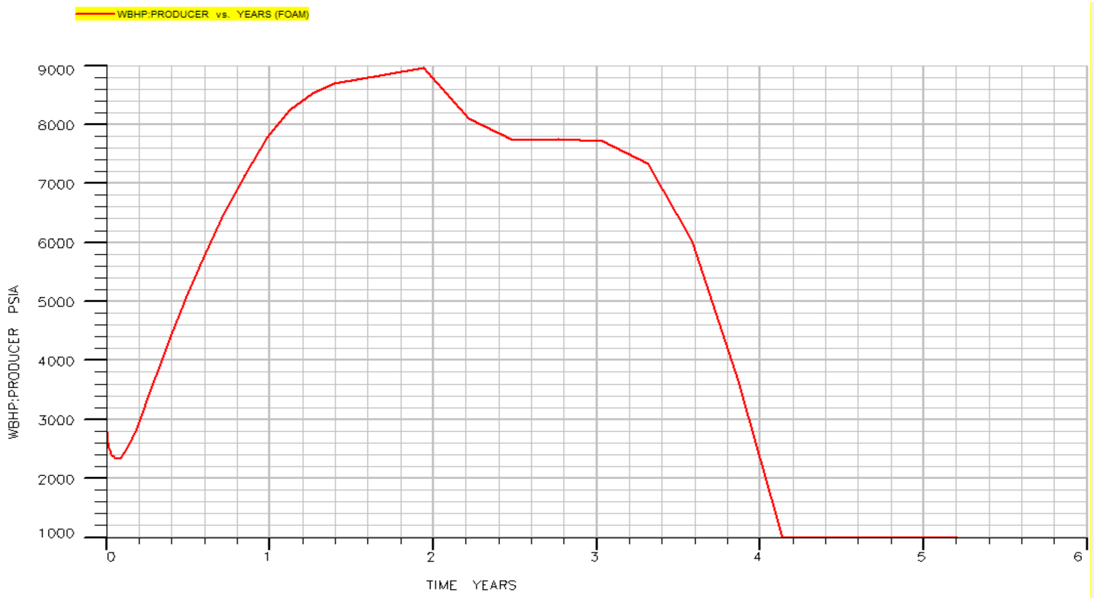

Figure 4.7: Bottom hole pressure at 8000 stb/d

Figure 4.4 – 4.7 show pressure distribution at different injection rate. Physically, the figures look similar and have the same trend. For each injection rate the pressure will be optimum at certain points where in this scenarios it will lead to maximum production rate. The pressure distribution graph does not shows a linear relation regards to the injection. This scenario implies that foam flooding has a drawback in terms of stability and thus giving the non-linear productivity index plot. The fluctuation of pressure happens in foam flooding due its adsorption and mechanical entrapment properties. The adsorption and mechanical entrapment occurs instantaneous and it is unpredictable in most situations.

The jumps on the plot corresponds to the higher production rate while the remaining part of the plot have an average recovery. Figure 4.4 show that at the rate of 2000 stb/d the maximum pressure will be 5300 psia at the 2.2 year. Beyond this point, the plot shows a drastic decrease in the pressure until 4.1 year and the pressure becomes constant until the end of production year 2034.

Figures 4.5 and 4.6 shows the same trend in the plot as fig 4.4. In both figures, as the injection rate is increased, the pressure also increases where in this case for injection rate of 4000 stb/day the maximum pressure will be 7225 psia and for injection rate of 6000 stb/day, the maximum pressure will be 8200 psia. It should be note that, the production life for both the injection rate last until the 19 years.

Figure 4.7 shows the highest injection rate which was run in the simulation. In fig 4.7 the injection rate was 8000 stb/d. Under this injection rate, the produced pressure plot was totally different from the previous plot. The plot shows that at the rate of 8000 stb/d the optimum pressure will be 9000 psia but the pressure is lost after 5.4 year. The pressure did not become constant like in the previous plots and at the same time it did not last until the 19 years. Eventually, this implies that after the 5.4 year there will be no production. Following are the results of production rate at different injection rates.

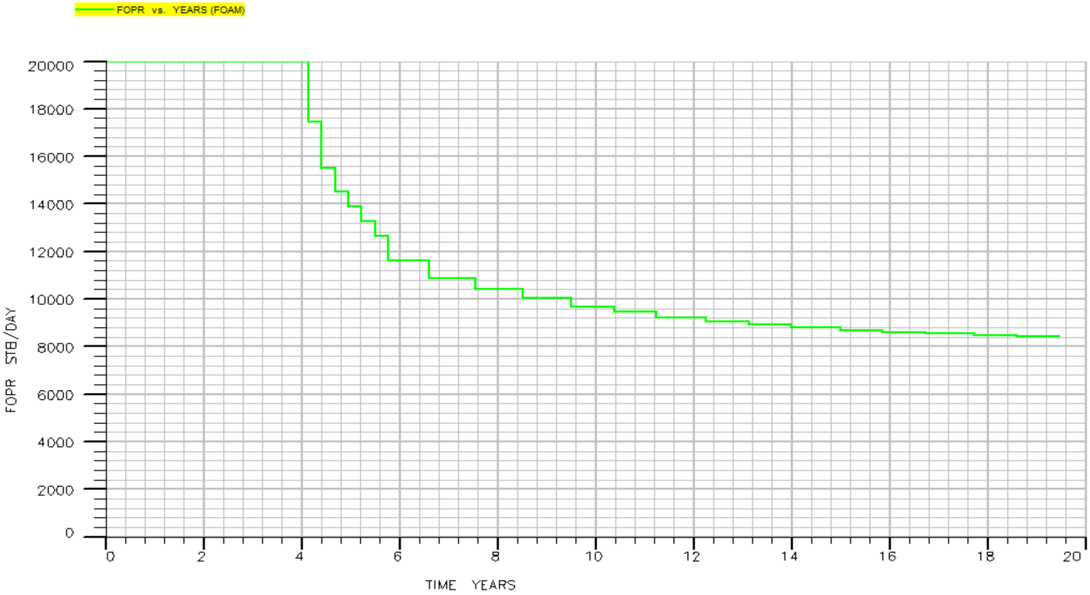

Figure 4.8: Production rate at initial rate of 1000 stb/d

At the initial rate of 1000 stb/d, the pressure available was sufficient enough to give oil production. The production life was available until the 19th year. The production life follows accordance to the pressure distribution as indicated in the fig 4.3.

The production rate for the injection rate of 2000 stb/d, 4000 stb/d, 6000 stb/d and 8000 stb/d are as follows:

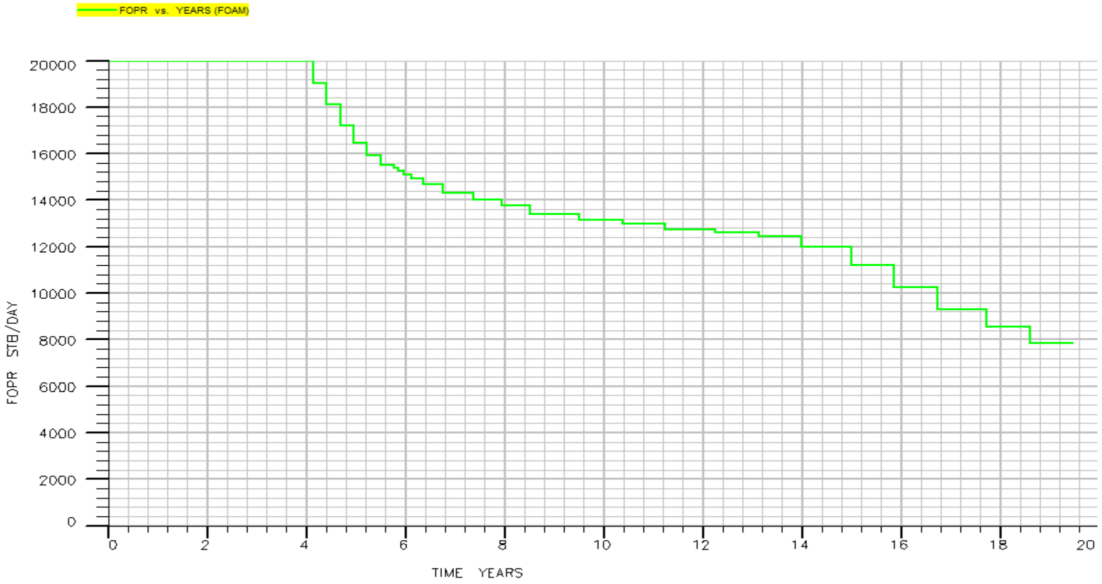

Figure 4.9: Production rate at 2000 stb/d

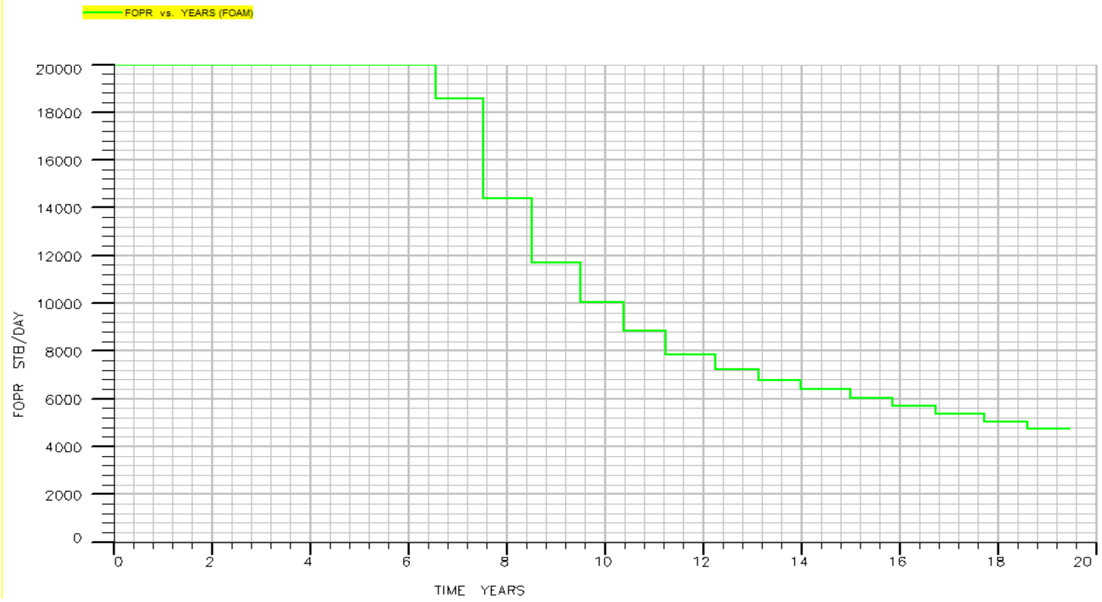

Figure 4.10: Production rate at 4000 stb/d

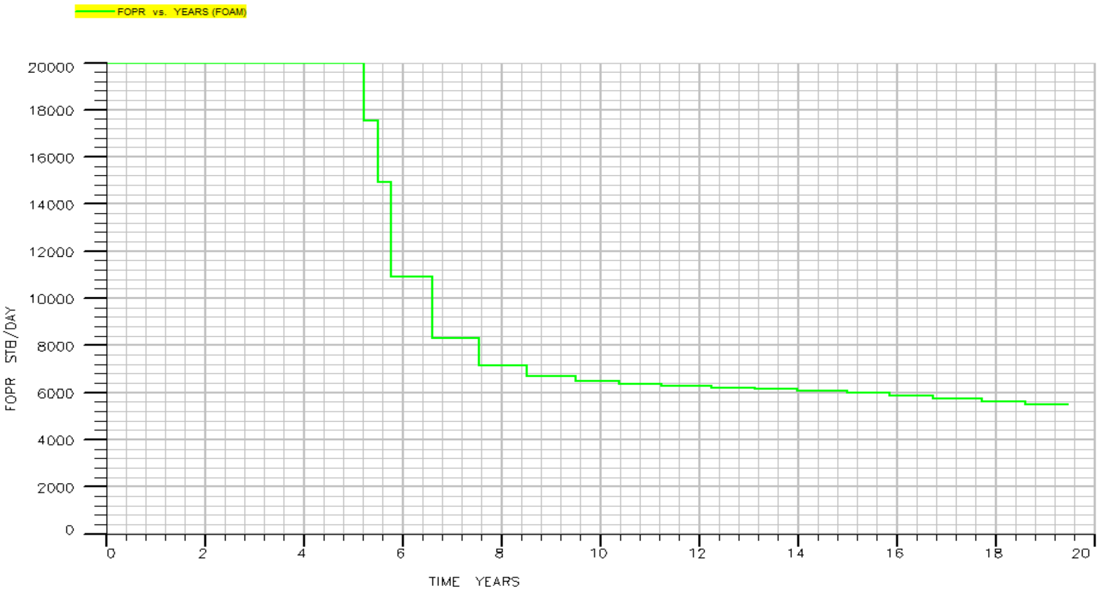

Figure 4.11: Production rate at 6000 stb/d

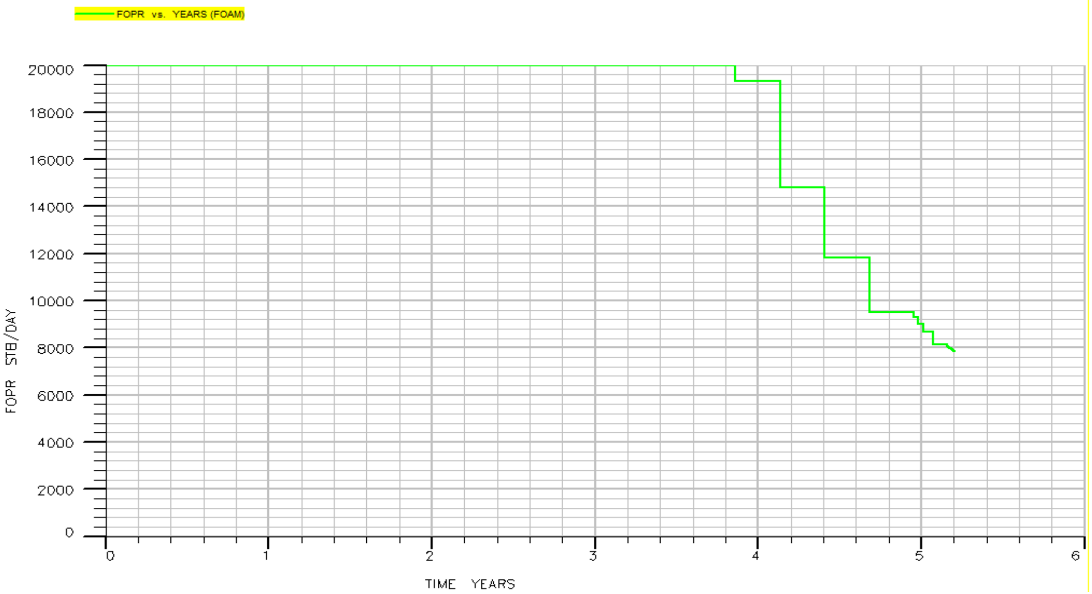

Figure 4.12: Production rate at 8000 stb/d

From the above observations, fig 4.9 – 4.11 shows that the production life last for 19 years. However, simulation result shows that in fig 4.12 the production did not sustain longer and stops after five years. Careful examination in the figures shows that the rate decline is stepwise trend. The production in figure 4.12 did not sustain until the final year since there is no pressure after five years for the injection rate of 8000 stb/d as indicated in the fig 4.7.

The pressure and the production profile will be different when the permeability varies. The following fig 4.13 and 4.14 show the pressure and production profile when the permeability is 200mD. While, fig 4.15 and 4.16 show the pressure and production profile when the permeability is reduced to 30mD.

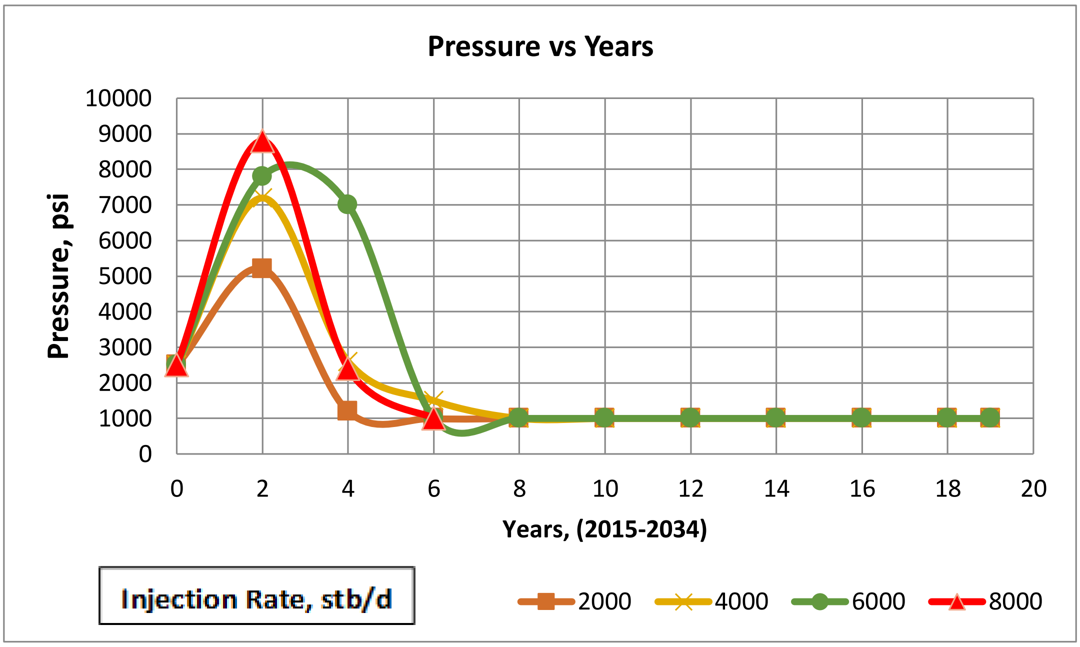

Figure 4.13: Pressure profile at high permeability

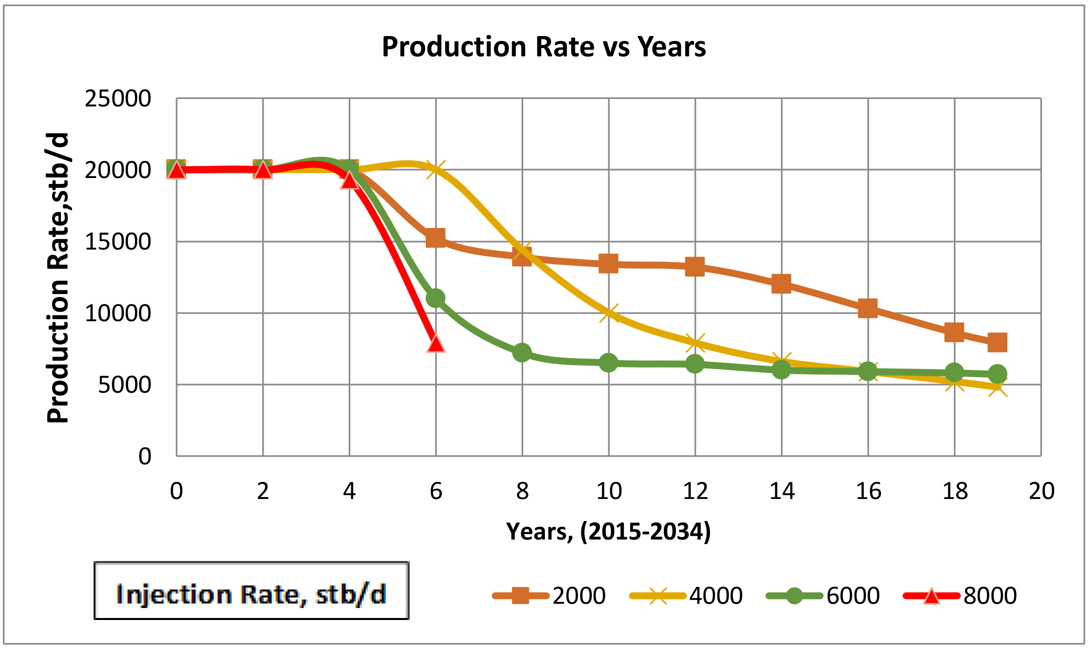

Figure 4.14: Production profile at high permeability

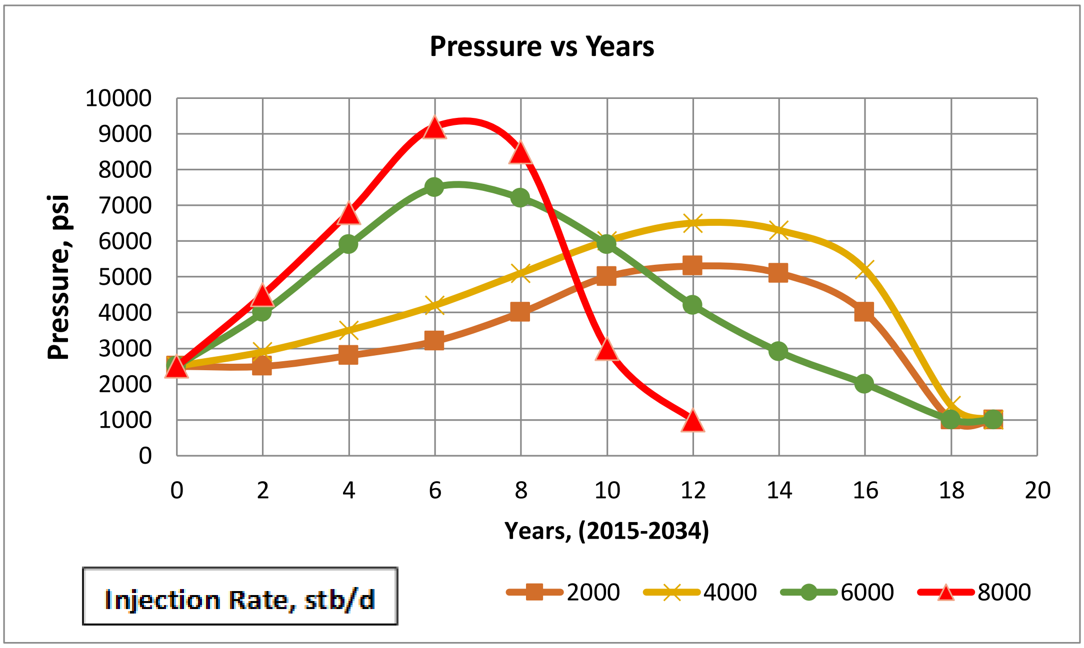

Figure 4.15: Pressure profile at low permeability

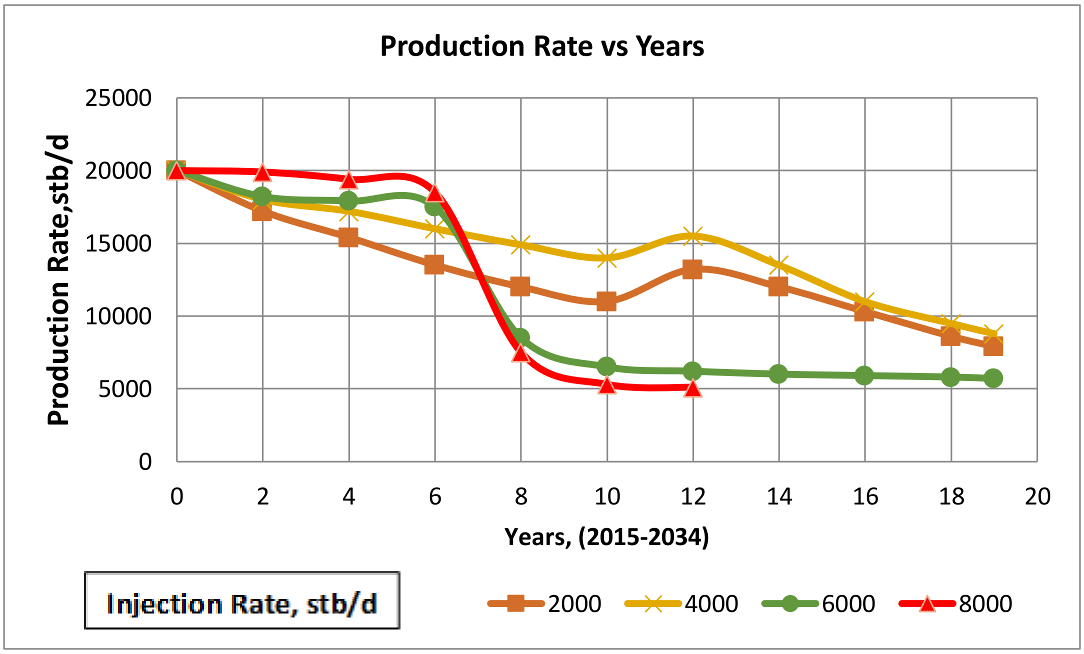

Figure 4.16: Production profile at low permeability

The foam stability can be analysed in terms of the pressure distribution per yer year. As the injection rate increases we can see the changes in the pressure profile. At high permeability, the foam propagates at very fast rate causing the increasing of pressure at the early stages of foam flooding. Since the high permeability provides a smooth flow path, the foam propagates without any obstacles and totally ruptures after five years at injection rate of 8000 stb/d. The graph is more feasible to be analysed when the permeability is reduced.

When the permeability is decreased from 200mD to 30mD, we can see the graph patterns changes. The graph shows a trend where the foam pressure will start to increases until an optimum point. The pressure start to declines after it reaches the optimum point. The foam ruptures after twelve years at the injection rate of 8000 stb/d. The graph has to be divided into several sections so the analysis can be done effectively.

The foam stability cannot be seen directly in the simulation process but it can be seen in detailed in the form of decaying rate. The foam decaying rate is known as the half-life of foam where it starts to rupture with per time.

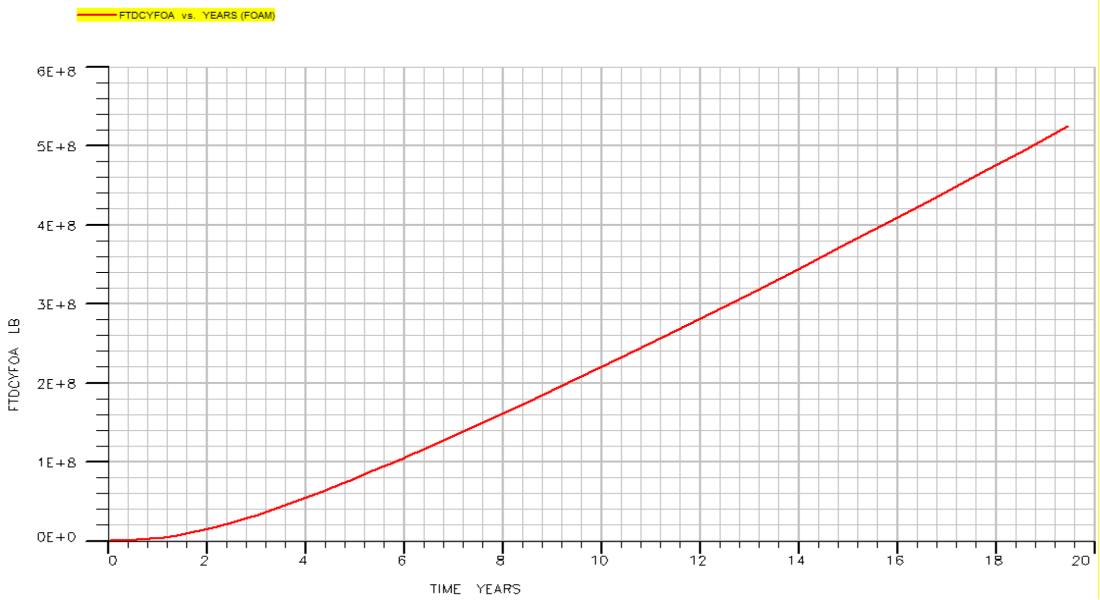

Figure 4.17: Decay rate at 2000 stb/d

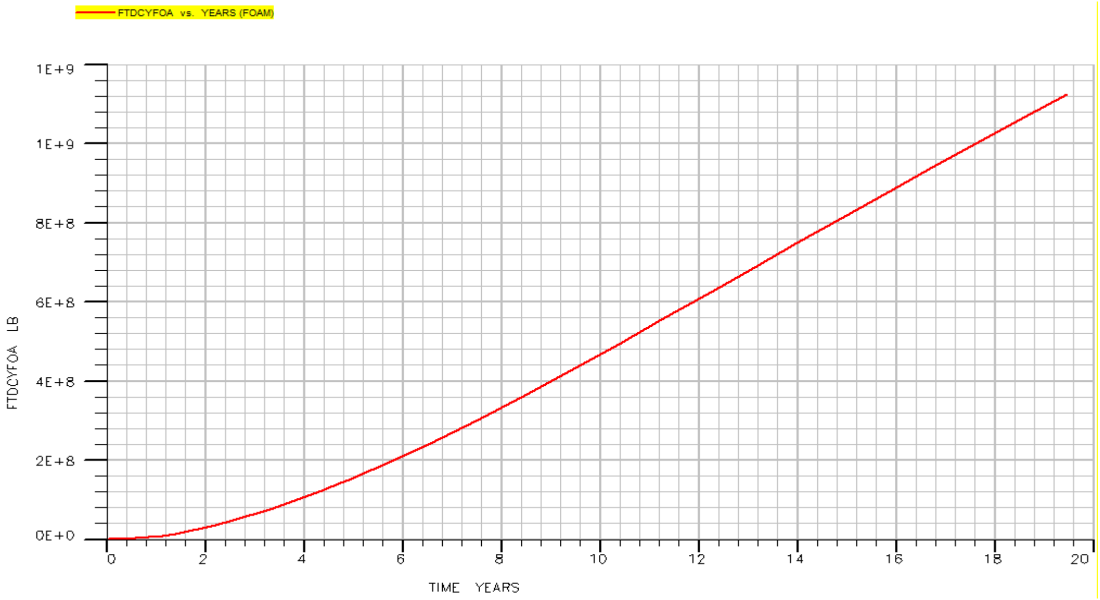

Figure 4.18: Decay rate at 4000 stb/d

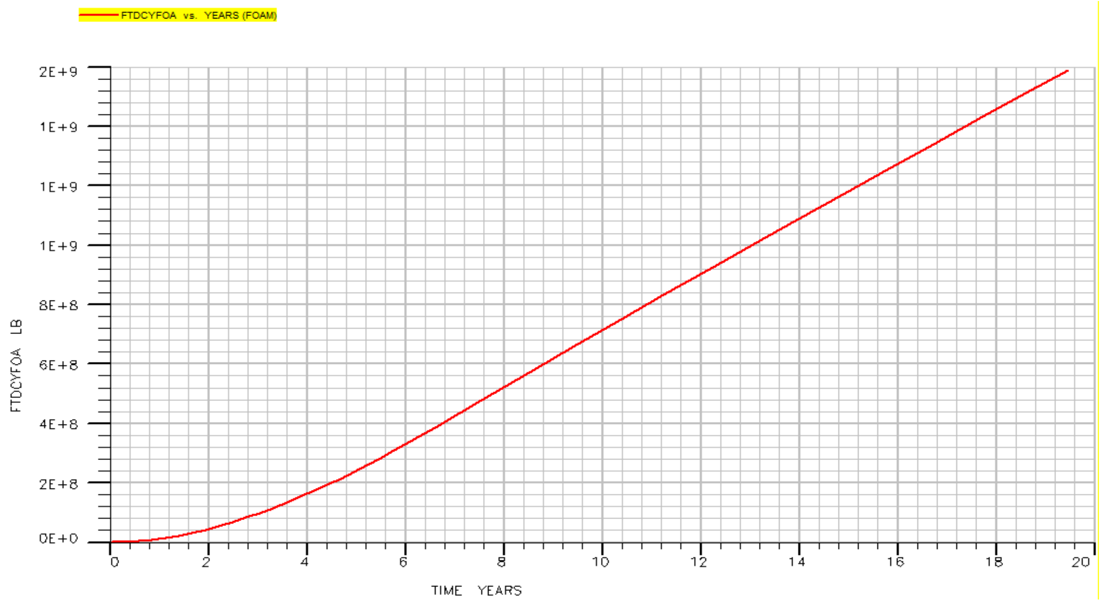

Figure 4.19: Decay rate at 6000 stb/d

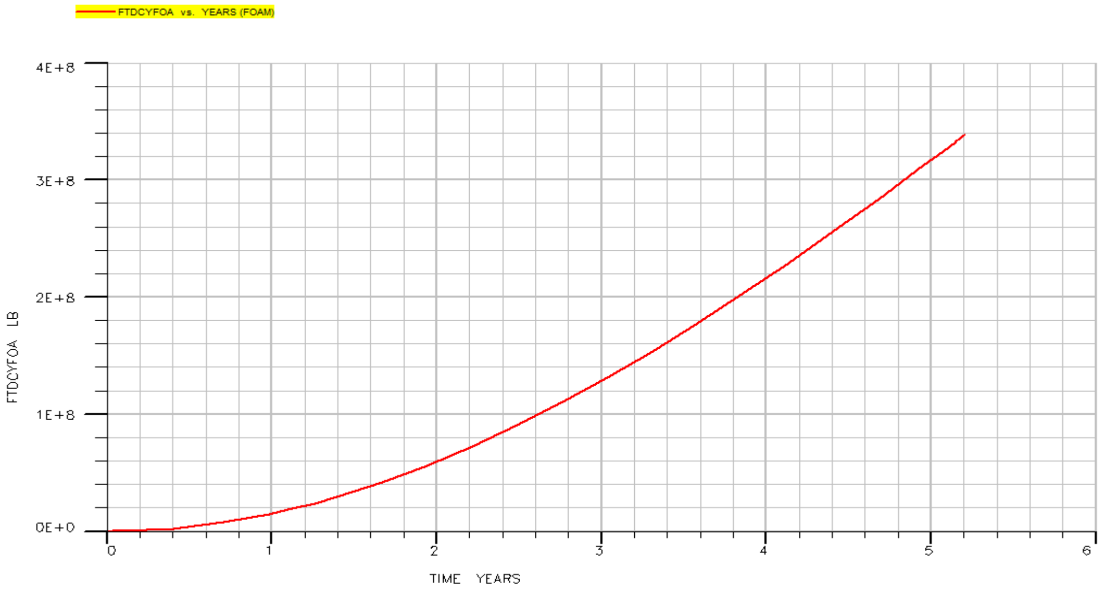

Figure 4.20: Decay rate at 8000 stb/d

Figure 4.17 – 4.20 depicts the decaying rate over foam flooding. Soon after the injection begins, the production will be higher at the initial stage but will gradually drops. This happens because as the foam propagates it tends to separate into aqueous and non-aqueous state. The hydrogen bonding that holds the gas and liquid bonding will not last longer as the injection proceeds. The hydrogen bonding will become weaker and the foam will starts separate into gas and liquid. This will cause the foam to destabilise and ruptures. The continuation of this rupturing process lead to less sweep efficiency and decrement in the production.

From the fig 4.17-4.19, the decaying rate occurs faster as the injection rate increase. Figure 4.20 shows that decaying rate stops at the year 5.2. This means that the foam has lost its stability and has rupture completely. There will be no foam after 5.2 years at the injection rate of 8000 stb/d. This implies that when the injection rate is higher, the foam decaying occurs at much higher rate in a very short time. On the one hand it is preferred to have high injection rates, so that large volumes of foam can be injected quickly and initiate the propagation faster. Figure 4.12 shows that the production begins to declines at 3.82 years at high injection rate. In this project, the fracture pressure will be 9500 psia and the most optimum pressure from the simulation is 9000 psia where it is still under the safety zone.

Comparing the results obtained for different injection rate, it confirms that foam provides good sweep efficiently and thus leads to optimum production rate. However, the stabilisation factor of foam becomes inconsistent when the injection rate increases. The stabilisation of foam can be improved if the adsorption and mechanical entrapment factor are removed. But, practically it may not be possible since this process cannot be avoided from occurring in the reservoir.

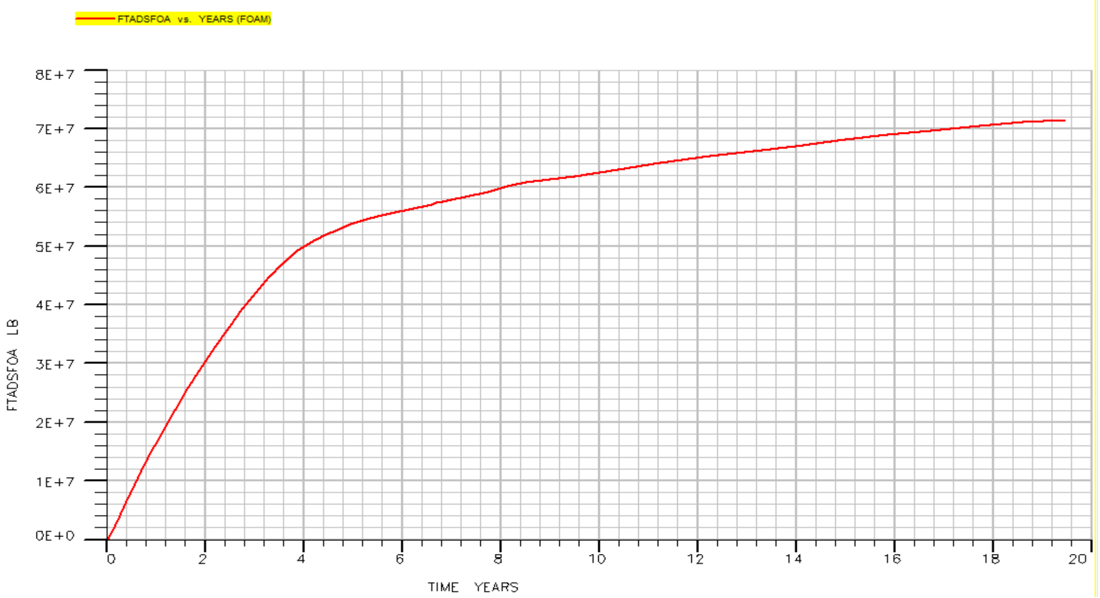

Figure 4.21: Adsorption factor at 2000 stb/d

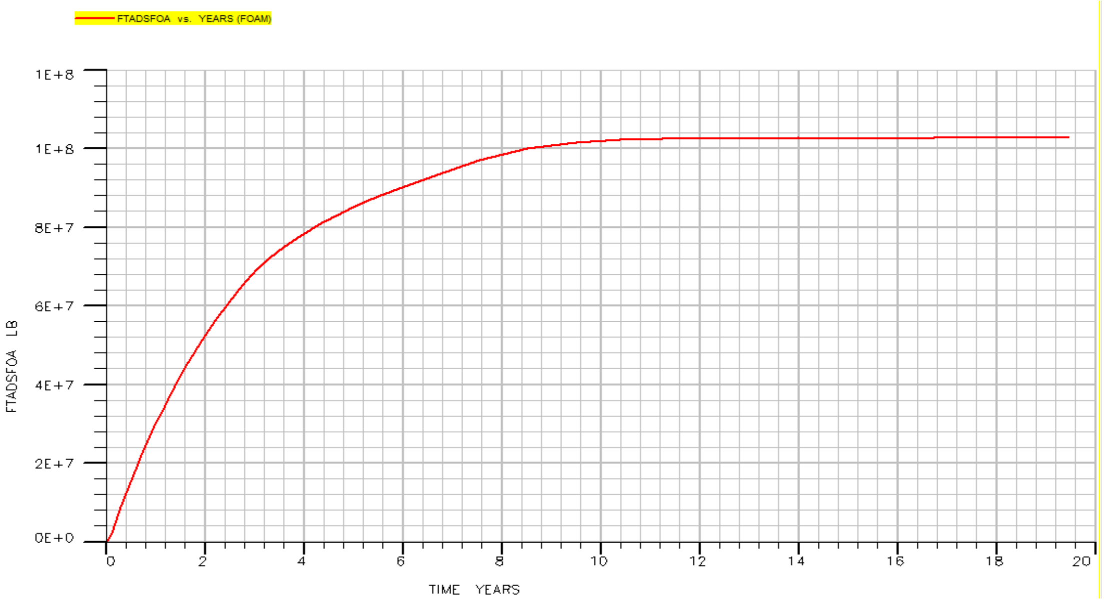

Figure 4.22: Adsorption factor at 4000 stb/d

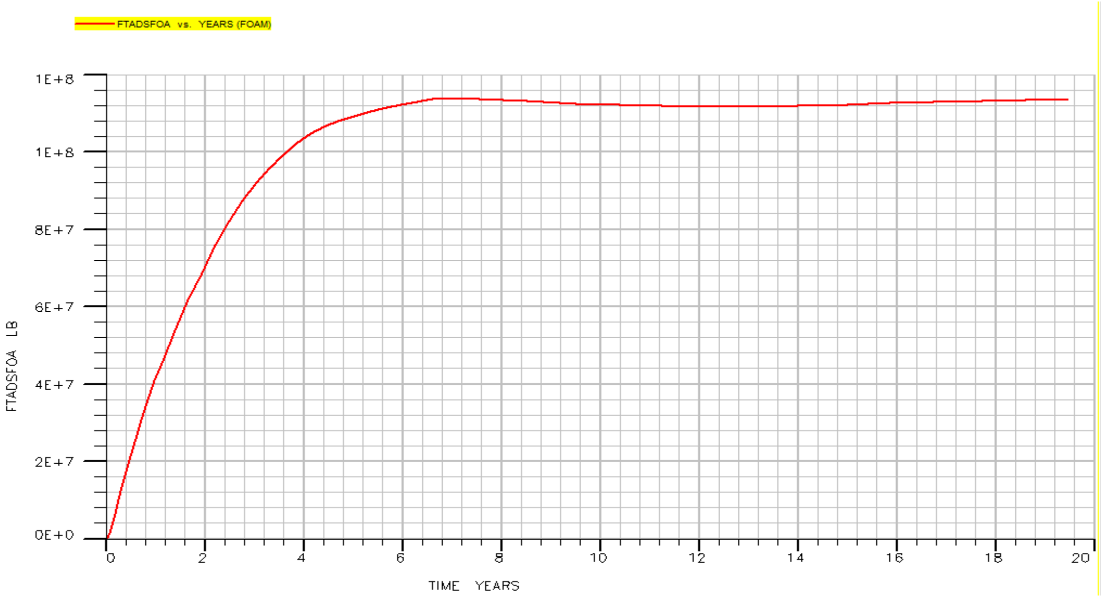

Figure 4.23: Adsorption factor at 6000 stb/d

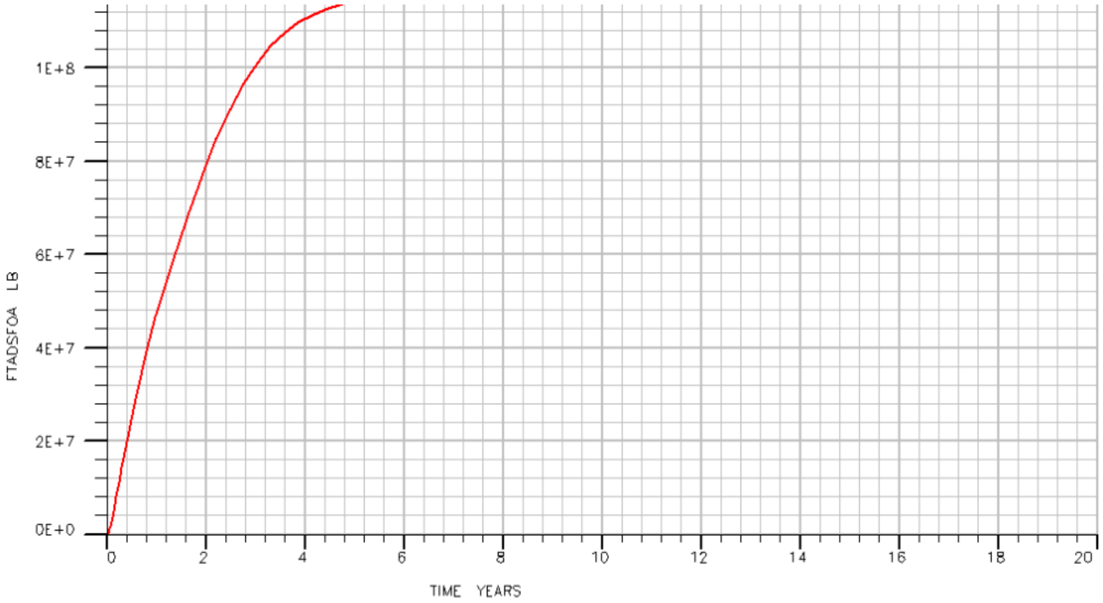

Figure 4.24: Adsorption factor at 8000 stb/d

Figure 4.21 – 4.24 shows the adsorption factor for the injection rate of 2000 stb/d, 4000 stb/d, 6000 stb/d and 8000 stb/d. At the lowest injection rate of 2000 stb/d, the values of adsorption factor keeps increasing until the 19th year. However, there is change in the graph as depicted in the fig 4.22-4.23 where the graph line increases until several years and becomes constant.

This happens because, at the lowest injection rate (fig 4.21) the dispersion occurs slowly and thus it causes the adsorption factor values to keep on increasing. Meanwhile, as the injection rate increases the dispersion occurs very fast causing the water and gas to separate at higher rate. Since foam separates into two phases, the adsorption process will occur slower causing a constant values.

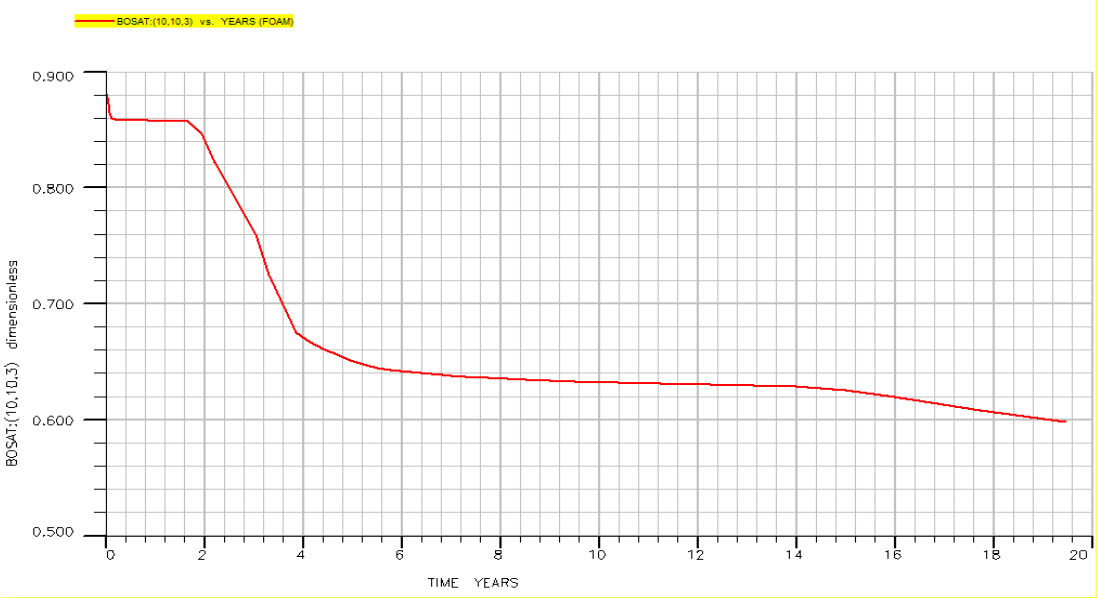

Figure 4.25: Oil saturation at 2000 stb/d

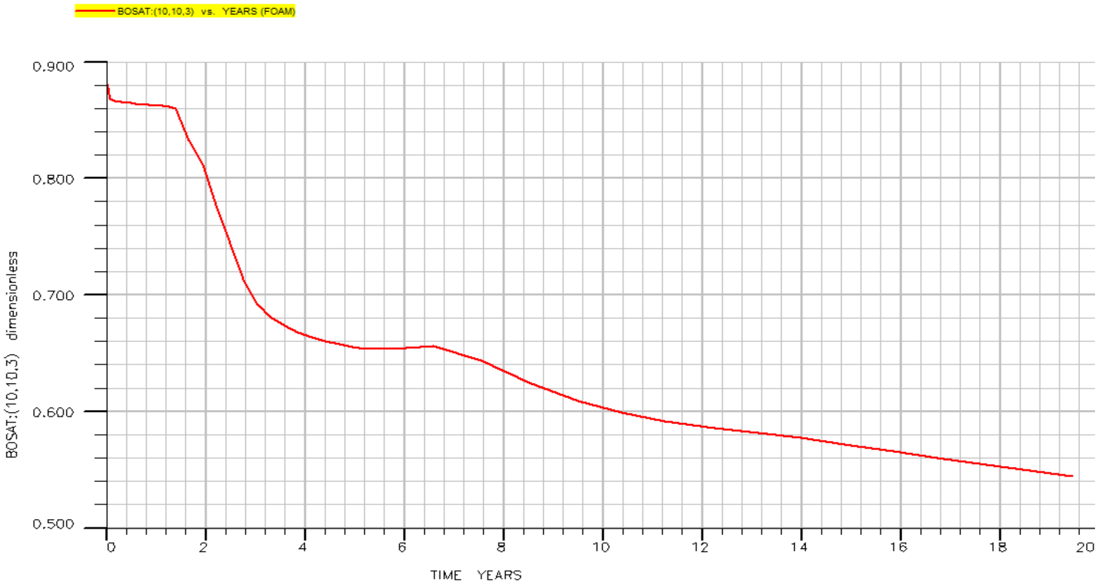

Figure 4.26: Oil saturation at 4000 stb/d

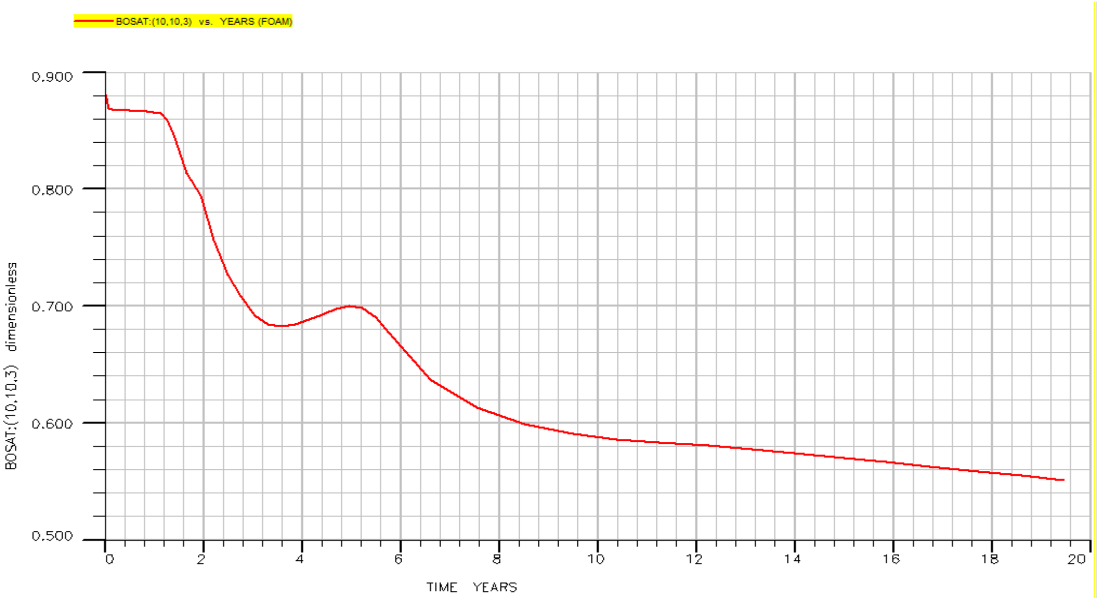

Figure 4.27: Oil saturation at 6000 stb/d

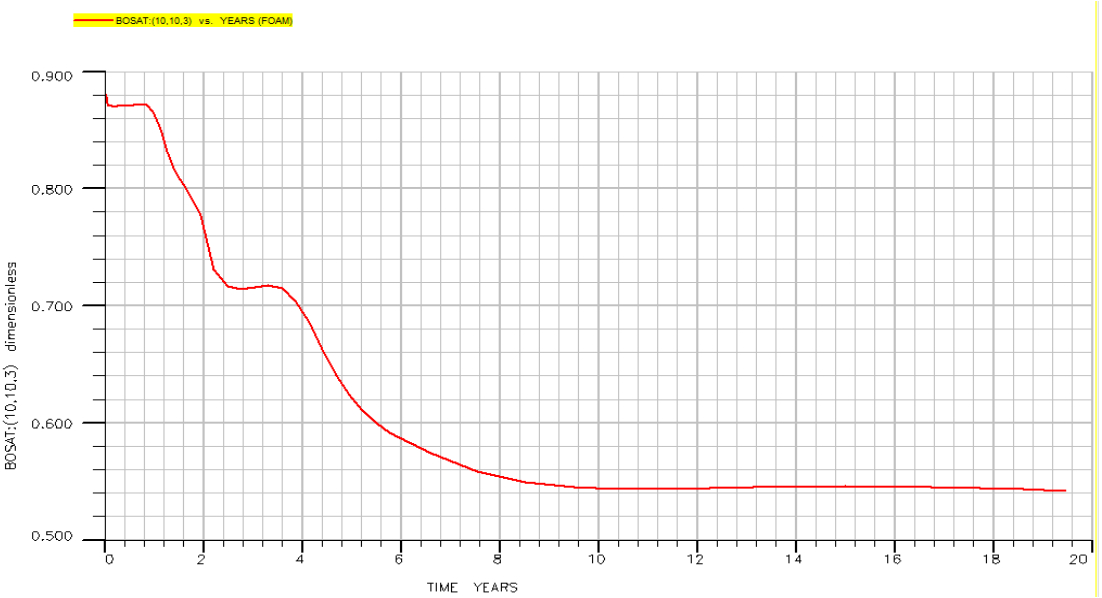

Figure 4.28: Oil saturation at 8000 stb/d

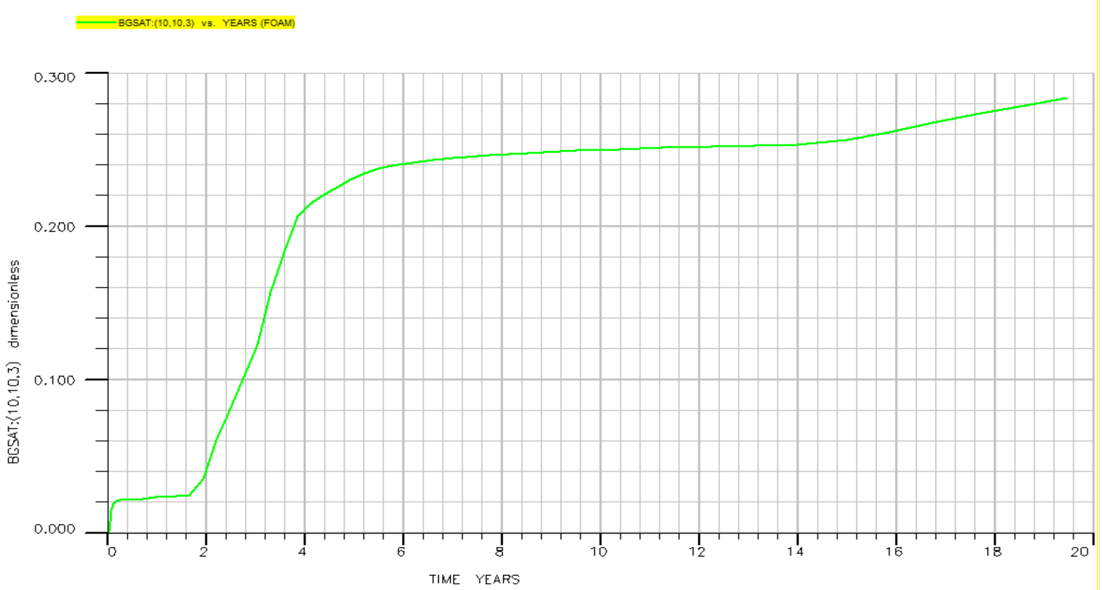

Figure 4.29: Gas saturation at 2000 stb/d

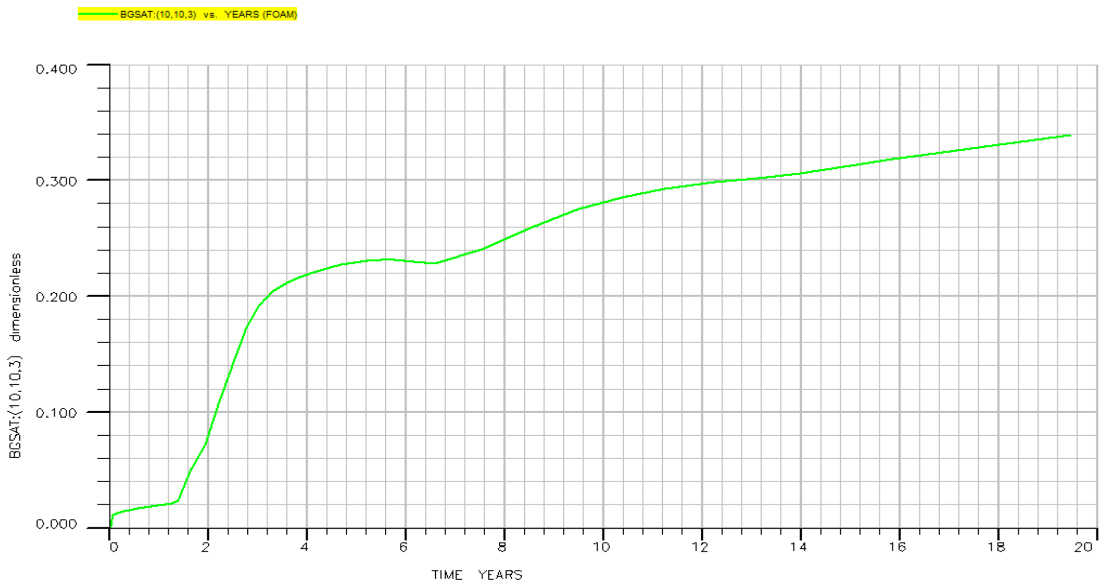

Figure 4.30: Gas saturation at 4000 stb/d

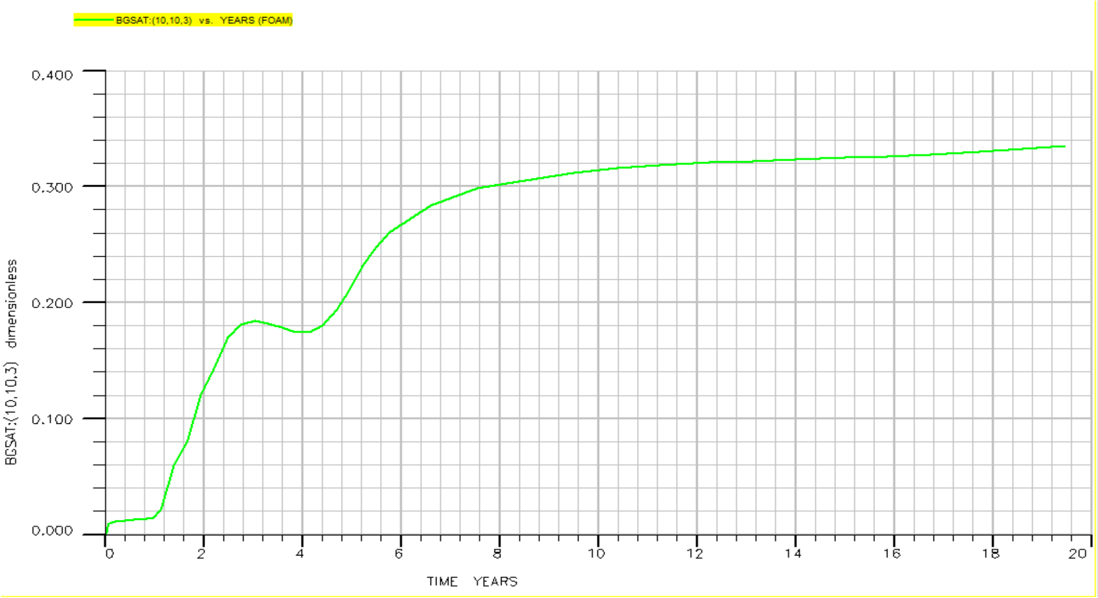

Figure 4.31: Gas saturation at 6000 stb/d

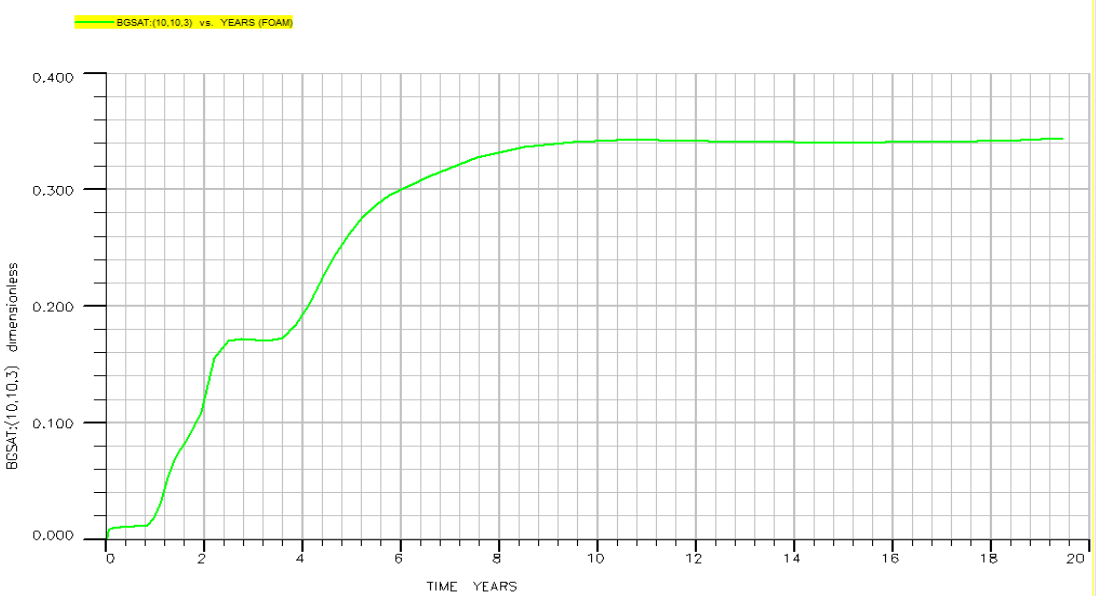

Figure 4.32: Gas saturation at 8000 stb/d

Figure 4.25 – 4.28 shows the oil saturation whereas fig 4.29 - 4.32 shows gas saturation at different injection rate. The oil saturation graphs shows decline at all injection rate while the gas saturation increases. When the foam comes in contact with the oil, the foam eventually destabilise causing oil saturation to decreases. The foam will be more favour when it comes contact with the gas. The gas will not cause the foam to destabilise. Thus, the foam will be still stabilised condition causing the gas saturation to increase. Nevertheless, the oil saturation values is higher compared to the gas saturation in almost all injection rate.

After analysing the parameters affecting the foam, the simulation was run using a stabilising agent. The base case was modified to input the stabilising agent parameter. The function of a stabilising agent is to stabilise the foam. The stabilising agent that was used in this project was surfactant. The function of surfactant is to prevent the foam from dispersing. The following graphs implies the results in terms of pressure and production after surfactant has been added.

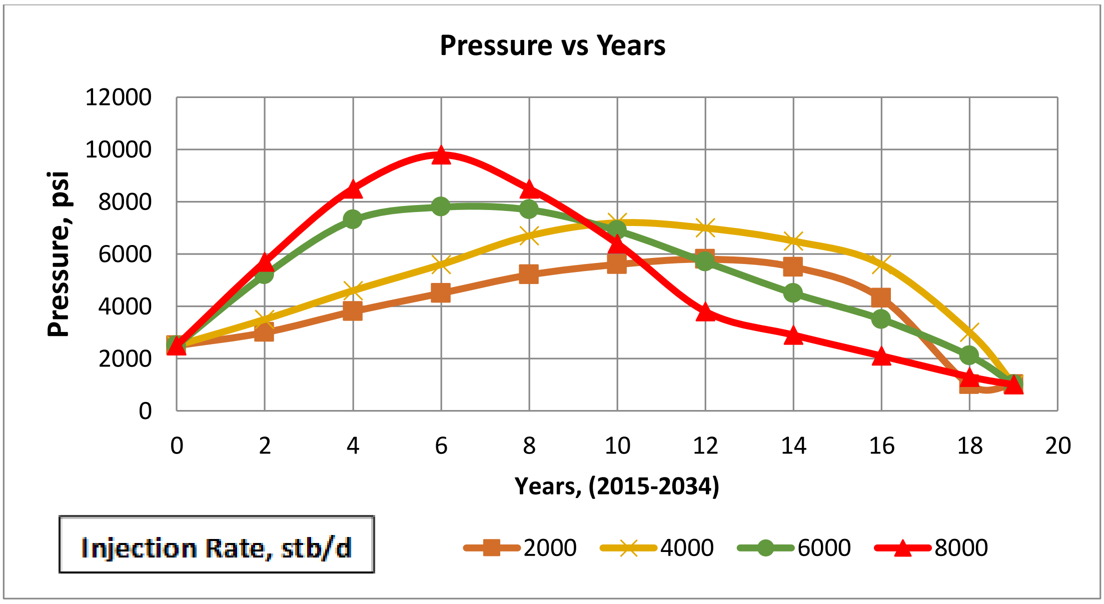

Figure 4.33: Pressure profile after adding surfactant

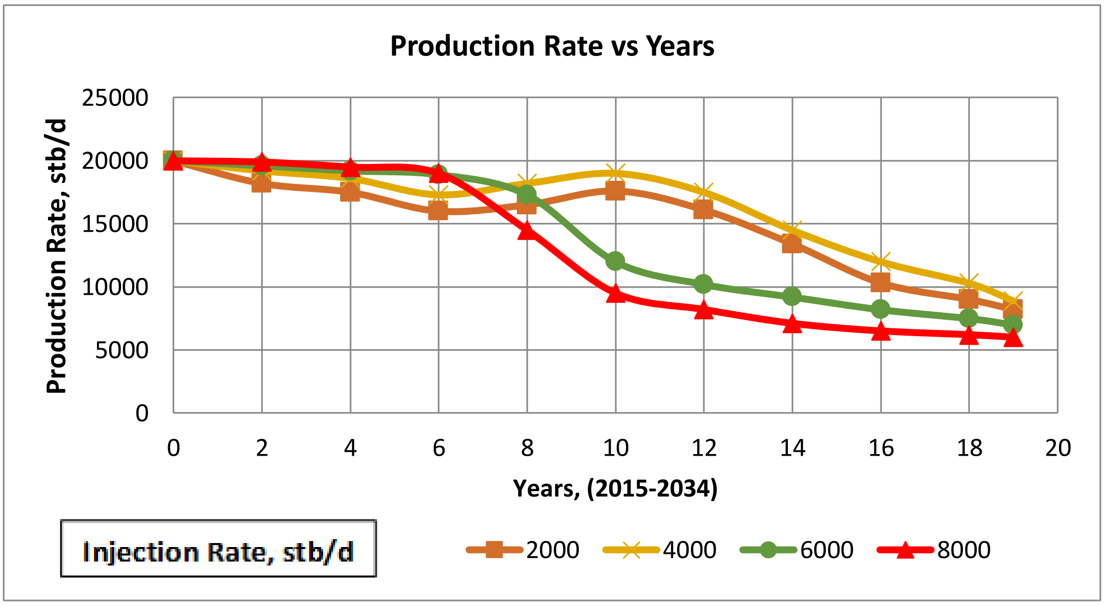

Figure 4.34: Production profile after adding surfactant

Figure 4.33 -4.34 shows the pressure and production profile after surfactant has been added as the stabilising agent. After adding the surfactant, the pressure and production profile shows a good improvement. In fig 4.14, the production stops after 5 years while in fig 4.16 the production stops after 12 years. But, in fig 4.34, the production was maintained until the last 19 years even at highest injection rate. Although, at highest injection the pressure drops down drastically, it still able to maintain the production until the final year. This happens because the surfactant reduces the dispersion of foam causing the foam to maintain it phase for a maximum number of years.

CHAPTER 5.0

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As a conclusion, the study met its objectives, which are to model foam propagation and pressure distribution during foam flooding operation, to evaluate the foam decaying rate at various rate of injection parameters and to investigate factors that affects foam stability.

The quantitative results implies that the foam has good sweep efficiency in almost all different injection rate. The study shows that the foam always propagate at any injection rates no matter what injection foam qualities were applied. The foam loses its complete stability when the foam is being injected at extremely higher injection rate. The higher injection rate causes the foam to undergo complete destruction within a short time range. The study gives an indication where the production rate can be improved if a stabilising agent is added to stabilise the foam from dispersing.

The foam simulation study in Enhance Oil Recovery should be in more systemic way to ensure that unnecessary waste can be avoidable during the injection process. It should be noted that the simulation results will not be the exactly same as the real life reservoir results since simulation performance mainly depend on the quality of data input. However, the foam simulation will able to predict future production accurately with the quality of data input is enhanced.

5.2 Recommendation

For more accurate and real results it is recommended detailed laboratory work. Experimental analyse should be conducted to get results on the factors that could not be analysed in the simulation. The change of foam dispersion can be analysed from Backscattering Physical Model.

The foam simulation and experimental study should be carried out with different types of stabilising agent. There are more stabilizing agents which can improve the foam efficiency. The factors that are affected after adding stabilizing agent should be analysed. Careful study should be carried out to find what kind of stabilizing agent is suitable for foam and how much concentration of stabilising agent is required.

In the future, complete economic analysis for foam injection should be done to optimize what kind of reservoir condition is applicable, when is the best time to begin the foam injection and what kind of well schedule cycles will achieve the most recovery with least time.

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