A Study of Foam Generation across Vertical Heterogeneity

by

Ulugbek Djuraev

14180

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
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Petroleum Engineering Programme

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In partial fulfillment of the requirement for the

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Approved by,

____

(Dr. Masoud Rashidi)

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

Ulugbek Djuraev

ABSTRACT

Generation of foam has proved to be very effective as a conformance material when it is used in gas injection processes to improve recovery of oil. Many various studies have been performed and valuable conclusions have been drawn to augment understanding about foam generation process and its impact on ultimate recovery. However, a heterogeneous nature in vertical direction imposes a “threat” or an “opportunity” for generation process. This challenge indeed creates a need to investigate comprehensively, which essentially is the problem statement of this study. Therefore, the objectives of this study are to investigate the effect of vertical heterogeneity on foam generation during gas injection processes, analyze and discuss the influence of foam generation on gas mobility, and most importantly on ultimate oil recovery efficiency. The groundwork of this paper covers fundamental knowledge on foam generation in a porous medium, and effect of vertical heterogeneity upon it. This study seeks to accomplish its goal by using computer simulations, whereby simulation cases are prepared with respect to the paper objectives. The results suggest that foam generation was not beneficial when it was applied in the reservoir with low – permeability layer on top of the high – permeable one. It failed to challenge the conventional gas injection process with respect to case studies developed in the project, as very little or no strong foam was generated. By contrast, as the foam was generated in the reservoir with high – permeability on top, and low – permeable layer in the bottom, it succeeded to control the gas oil – ratio and mobility of injected gases quite effectively. Nevertheless, the most important benefit of foam was when it was generated at permeability contrast ratio of four, and foam proved to be even more beneficial to recover more oil at very abrupt contrast ratio of permeability between layers.

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ABBREVIATIONS AND NOMENCLATURES

$\mathbf{f_g}$	Gas quality
$\mathbf{g}$	Gravity constant
$\mathbf{k}$	Permeability
$\mathbf{k_h}$	Horizontal permeability
$\mathbf{k_v}$	Vertical permeability
$\mathbf{k_x}$	Permeability in x – direction
$\mathbf{k_y}$	Permeability in y – direction
$\mathbf{k_z}$	Permeability in z – direction
$\mathbf{N_g}$	Gravity number
$\mathbf{N_k}$	Permeability contrast ratio
mD	milliDarcy
$\mathbf{S_{gr}}$	Residual gas saturation
$\mathbf{S_w}$	Water saturation
$\mathbf{P_c^{sn}}$	Snap – off capillary pressure
$\mathbf{P_c^{e}}$	Entrance capillary pressure
$\boldsymbol{\mu_g}$	Gas viscosity
$\boldsymbol{\mu_w}$	Water viscosity
$\boldsymbol{\rho_g}$	Gas density
$\boldsymbol{\rho_w}$	Water density

CHAPTER 1

INTRODUCTION

1.1 Background

Generally, an oil field goes through several stages of recovery: primary, secondary and tertiary. Owing to vast industry experience, it is well known that primary and secondary recovery techniques can produce up to one third of the reservoir original oil in place. Various enhanced-oil-recovery techniques have been established to improve recovery of a reservoir that has been exploited by primary and secondary recovery methods. One of the commonly practiced methods is gas injection. In theory, gas injection method is capable of producing almost 100% of oil in place. In spite of this remarkable result, there are many inevitable complications which are almost impossible to avoid. In addition, due to a heterogeneous nature of the reservoir, low density and high mobility of the injected gas, the sweep efficiency is reduced. As a result, the ultimate recovery is drastically fallen. The tendency of the injected gas to rise to the reservoir top is a result of its low density and gravity override, resulting in early gas breakthrough. Moreover, high gas mobility tends to be viscously instable, which indeed augments gravity override and makes heterogeneity even worse by creating high-mobility flow paths (Shan and Rossen, 2002). The remedy of this complexity lies in the use of foam, where gas mobility and heterogeneity effects can be diminished, ultimately leading to improved sweep efficiency.

Pioneers, Bond and Helbrook (1958) were the first to propose to use foam for mobility control. According to the concept of foam for gas mobility reduction, the injected gas is trapped in bubbles and the movement of these bubbles is restricted. As a result, the trapped gas lessens relative permeability of gas, because liquid films (lamellae) impede flow channels. Consequently, the effective gas viscosity in the flowing bubbles is increased that causes significant drag (Renkema and Rossen, 2007). In the last few decades, there has been done much research to better grasp and explain the foam mechanics in porous media. The investigation of foam behavior has been carried out in computer simulation studies and core experiments. However, the majority of these experiments were run on homogeneous porous media, with a small number of experiments conducted in heterogeneous porous media.

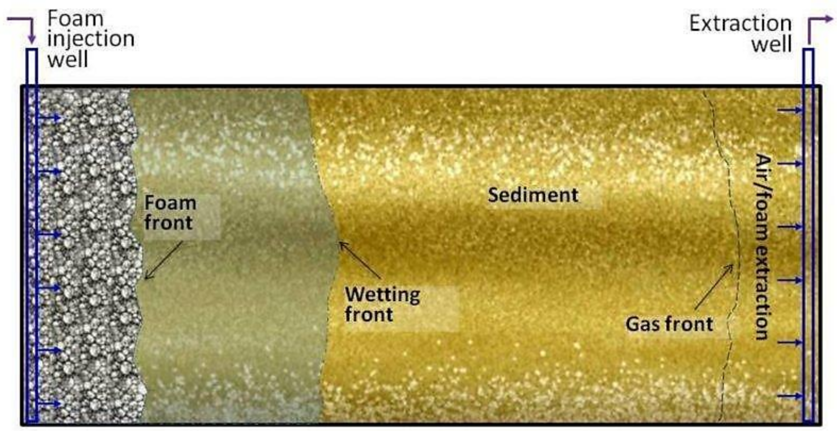


Figure 1.1: Foam Flooding Process (dl.sciencesocieties.org, 2014)

In practice, there is no homogeneous but heterogeneous nature of porous media. In injection processes for heterogeneous reservoirs, any displacement fluid will definitely enter high permeability layers. Therefore, the blocking effect of foam can be used to plug high permeability layers to improve flood front conformance so that medium and low permeability layers with high residual oil saturation would receive more injection fluids. This phenomenon is highly beneficial for improvement of ultimate recovery. Nonetheless, despite in-deep theoretical knowledge about foam generation and factors that govern the generation mechanism, it has been a real challenge to examine foam impact when employed across vertical heterogeneity of the reservoir. Hence, this paper provides insight on a heterogeneous reservoir performance under foam generation process for two different arrangements of vertical heterogeneity, where this heterogeneity would be alternated by changing the permeability ratio between the layers of the porous medium.

1.2 Problem Statement

Injection of gases are considered to be incredibly efficient in recovering additional oil from petroleum reservoirs. Unfortunately, it is known that in most cases, gas contacts and sweeps only a relatively small portion of the reservoir due natural behavior of gases (gravity override), and most importantly due to heterogeneity of a porous medium. Nonetheless, use of foam is practically proven to be an effective remedy to improve gas sweep. There have been successful foam experiments and simulation studies to investigate impact of foam flooding in heterogeneous reservoirs, where the emphasis was on vertical heterogeneity. On the other hand, a vertical heterogeneity of a porous medium may too impose challenges for foam generation processes, which is the problem statement of the study.

1.3 Objectives and Scope of Study

Objectives

→ To investigate whether vertical heterogeneity is a "threat" or an "opportunity" for foam generation process

→ To examine a reservoir performance affected by foam flow across vertical heterogeneity

→ To analyze and compare impact of foam generation during gas injection processes on ultimate recovery

Scope

The scope of this paper comprises of investigating foam generation impact of a reservoir performance with respect to the data and assumptions of the foam model. The work conducted is solely dedicated to achieve the objectives of the paper with respect to timeframe provided for the project. The scope of the project is focused on the permeability contrast between layers, where different arrangement of porous layers are employed. Therefore, the results obtained are limited to cases when the assumptions are valid, where the main focus is drawn at the ultimate recovery when foam generation process and sole gas injection are compared. There are many reasons why foam flooding might not be successful due to its instability and inability to propagate over large distances, including degradation and adsorption of surfactant, or insufficient injection pressure gradient over the given distance and etc. Therefore, the simulation model considers necessary data and assumptions that are applicable for the reservoir model used in this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Foam in Porous Medium

Even though foam is what seen in everyday life, foam in a porous differs from its other “bulk” forms. In a porous medium, the foam is defined as a gas dispersed in a liquid where the liquid is in continuous phase, whereas the gas is at least partly is discontinuous by lamellae (Hirasaki, 1989). Basically, this definition includes both bulk foams, where one’s bubble size is much smaller than the size of the pores; and the other one, whose average bubble size is greater than the pore dimensions. Foam is called “unstable” when the lamellae is short-lived, and longer-lived foams or “stable” foams that travel from pore to pore.

There are two main types of in-situ foam. Firstly, ‘weak’ or ‘continuous’ foam has at least one continuous gas channel (not interrupted by lamellae). The gas channel is coated with stationary lamellae which prevent gas flow across the static boundary. This means, that gas can flow without encountering or having to displace lamellae while flow through this so-called channel. However, the second class, which is called ‘strong’ or ‘discontinuous’ foam is the desired one in all improved oil recovery applications. This ‘strong’ foam is different from the ‘weak’ one by having lamellae in the channel, thus making it discontinuous over a certain distance (Falls *et al*., 1988) (Figure 2.1).

2.2 Foam generation mechanisms

There are three essential foam generation mechanisms: Leave – behind, Snap – off and Lamellae division. However, the generation of strong foam requires a snap-off process of foam generation mainly. (Rossen *et al*., 1999). As it is mentioned earlier, the desired form of foam, that is a discontinuous – gas foam generation entails a snap – off occurrence. In case of the snap – off, the non – wetting phase (invading gas) cross the threshold of a pore restriction initially filled with wetting liquid (surfactant solution).

The third mechanism, lamellae division, also contributes to formation of a strong foam. However, this mechanism as well as leave – behind one lay beyond the scope of this paper, and thus will not be discussed in details.

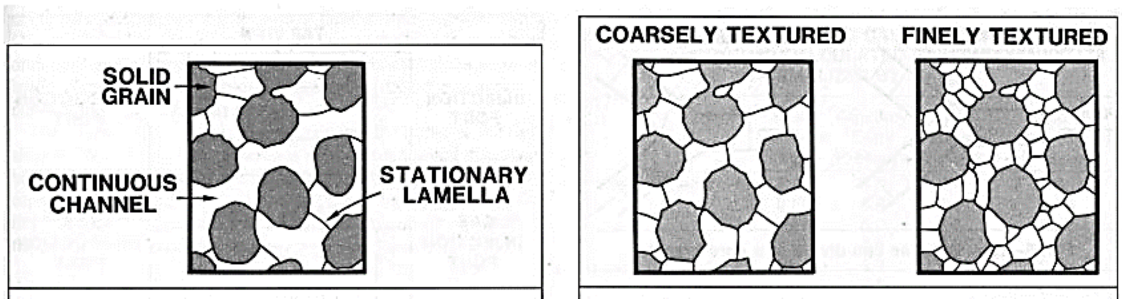


Figure 2.1: Continuous Foam (left) and Discontinuous Foam (right) (Falls et al., 1988)

2.2.1 Snap – off Foam Generation

As it was discussed earlier, there are three foam generation mechanism. Although the basic principles of each mechanisms were discussed briefly, the main focus remains of the snap – off mechanism. The importance of the snap – off mechanisms is that it is very vital at generating a "strong" foam. This was tested experimentally and observed (Falls *et al.*, 1988), and it was concluded that $P_c^{sn} \approx \frac{1}{2} P_c^e$ (Figure 2.2). Also, an important observation was drawn that the pore radius must be at least twice greater than the radius of pore throat, which in essence is compulsory to produce the needed reduction in capillary pressure to have strong foam (Tanzil *et al.*, 2002).

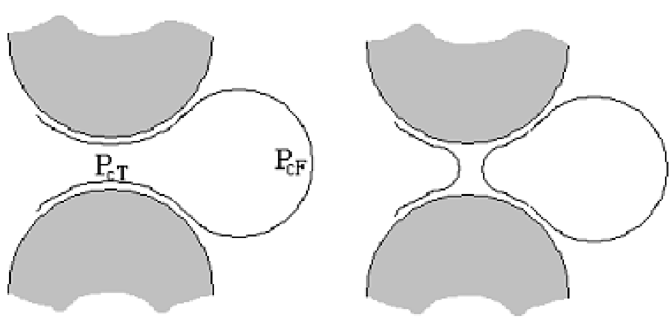


Figure 2.2: Snap-off Foam Generation (Tanzil et al., 2000)

2.2.2 Required Permeability Contrast

The required permeability contrast plays a crucial role in this paper. Despite having an increase in permeability between layers, a certain critical value should exist in order to be able to simulate real applications of foam generation more accurately. In the paper presented by Tanzil *et al*. (2000), a consensus was achieved by deriving mathematical expressions that quantified the desired critical number. The snap – off takes place at an abrupt increase in permeability between layers the permeability contrast must be at least four. Figures 2.3 and 2.4 present a graphical illustration of the process.

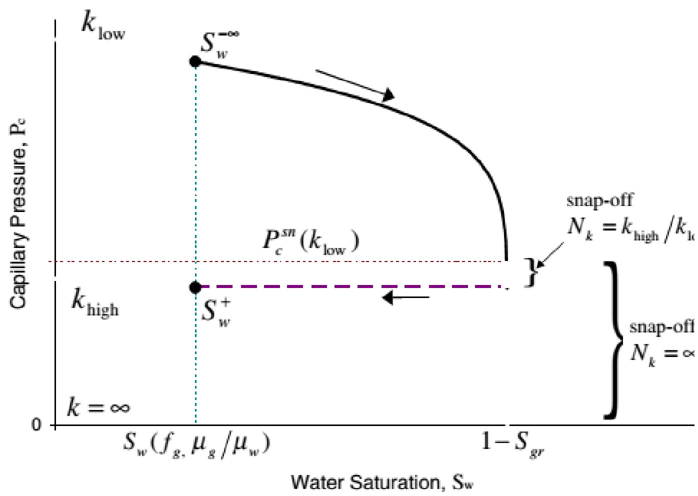


Figure 2.3: Snap-off Mechanism at Sudden Permeability Increase (Tanzil et al., 2002)

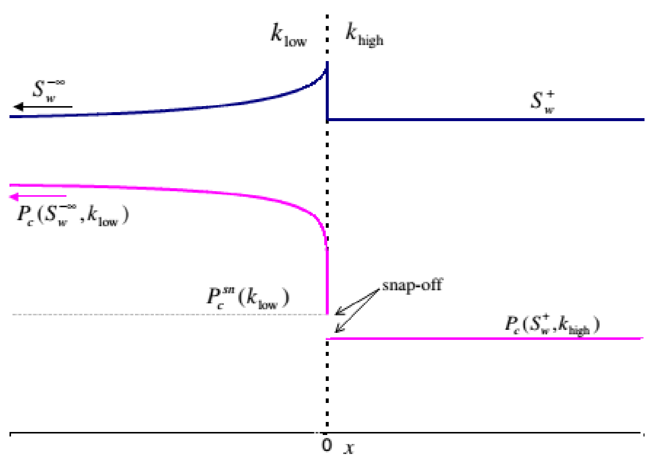


Figure 2.4: A Snap-off Mechanism: A Different Perspective (Tanzil et al., 2002)

2.2.3 Foam Generation at Abrupt Permeability Increase

Another empirical study was conducted to investigate foam generation and flow in a horizontal heterogeneous and homogeneous porous mediums. The graphical illustration is provided below. For the record, the experiment conducted below was at $f_g = 0.67(67\%)$ and $u_g = 5$ feet/day.

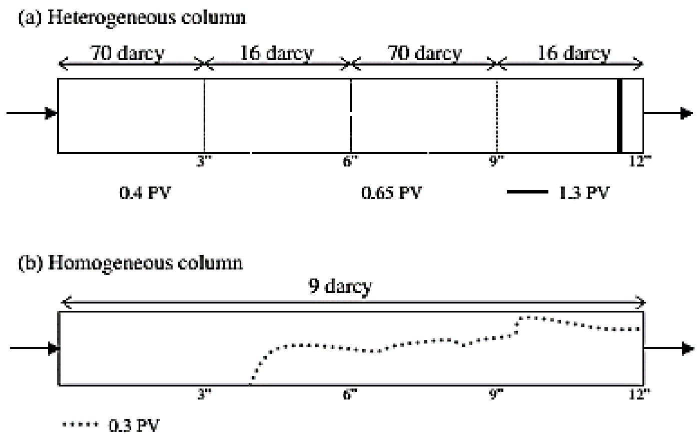


Figure 2.5: Foam Flood Fronts in (a) Horizontal Heterogeneous, (b) Horizontal Homogeneous Sand-packs (Tanzil et al., 2002)

As it can be observed from the figure above, the required permeability contrast between layers of four was definitely met in Part a. The piston-like movement of the gas front was not obtained till gas reached the boundary of desired permeability contrast in the third section. Thereafter, a piston-like movement was achieved until the end of the sand-pack, where the gas began to breakthrough. In spite of the gas break through, the pressure drop sufficiently high as can be observed in Figure 2.6. By contrast, a completely different outcome was obtained when same procedure was repeated on homogeneous sand-pack, which had an early breakthrough due to gas gravity override. The pressure drop for homogeneous sand-pack was not satisfying.

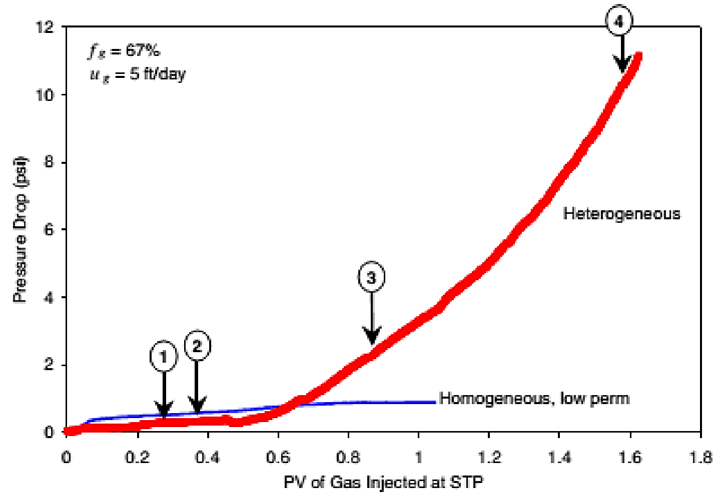


Figure 2.6: Pressure Drop during Foam Flooding Experiments. (Tanzil et al., 2002)

2.3 Factors Affecting Foam Generation across Vertical Heterogeneity

There is a number of factors that affect the foam generation process in a porous medium. However, the scope of the project revolves around basic factors such as permeability contrast ratio with respect to capillary effects in a multiphase flow, vertical upward flow and effect of vertical permeability on flood front in foam SAG displacements.

2.3.1 Capillary Effects in Multiphase Flow

For any flow type of multiphase fluids, the capillarity effects play a key role in heterogeneous (layered) porous medium, as low flow rates are employed, and contrasts of permeability are significant over short distances. Such scenario is usually encountered in many reservoirs (Tanzil *et al.*, 2000). Because capillarity is the cause when the non – wetting (gas) phase being trapped in regions of high – permeable, capillary entrapment drastically affect oil recovery. Additionally, capillarity forces obstruct non – wetting fluid cross – flow. Sharp permeability capillarity has significant effects at cross – flow perpendicular to a strata (Chaouche *et al.*, 1993). It was mentioned that the following pressure drop across regions of sudden permeability increased which produces snap – off (van Lingen, 1998). Thus, it makes a snap – off to be significant to flow of in heterogeneous porous medium at the sudden permeability increased contrast. Moreover, with the surfactant existence, generation of snap – off foam can significantly diminish gas mobility (Tanzil *et al*., 2000).

2.3.2 Vertical Upward Flow

Tanzil *et al*. (2002) argued that foam generation by snap-off mechanism is crucial under influence of gravity force, specifically as the gas travels vertically upward. They claimed that this phenomenon can be explained by stating the following inequality below:

$$\mathbf{N_g > \left(1 + \frac{P_c^e - P_c^{sn}}{\Delta p_g}\right)} \quad \textbf{(1)}$$

$$\textbf{where } \mathbf{N_g \equiv \frac{\Delta\rho g h}{\Delta p_g}}$$

In fact, foam can be produced more evenly uniform across the layer for the period of the vertical flow, given that the gravity override is not considered. It is agreed that in order for gravity to allow a snap-off to befall, N_g (the gravity number) should be satisfactorily great. Thus, a performed by them an experiment shows a solid prove of that theory. It was considered, that 290 Darcy 1 foot long column was first laid horizontally and then vertically to conduct the experiment. The superficial velocity of gas was same in both cases, 120 ft/day. The illustration of the result is below.

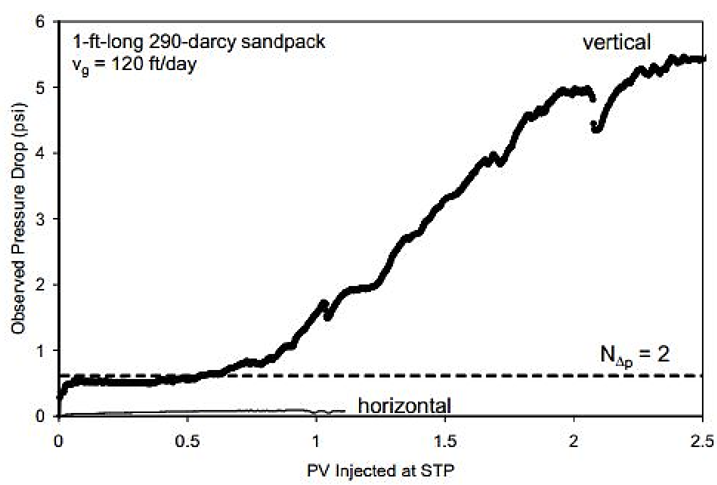


Figure 2.7: Pressure Drop in Horizontal and Vertical Sand-packs (Tanzil et al., 2002)

2.3.3 Effect of Vertical Permeability on Flood Front in Foam SAG Displacements

The preceding sections of this chapter discussed the basic mechanisms behind foam generation in a porous medium. Research of de Velde Harsenhorst *et al.* (2013) extended the model of Shan and Rossen (2004) where they studied the impact of the relationship between vertical and horizontal permeability values over a large inter-well distance. They discovered that if k_v decreased, the gravity segregation worsened. The conclusion was that with larger values of k_v foam pushed gas in downward direction in response to the pressure difference across the foam front. In other words, as the ratio $\frac{k_v}{k_h} < 1$ and not zero, the flood front would be able to sweep vertically more uniformly. A graphical illustration of this phenomenon is provided below.

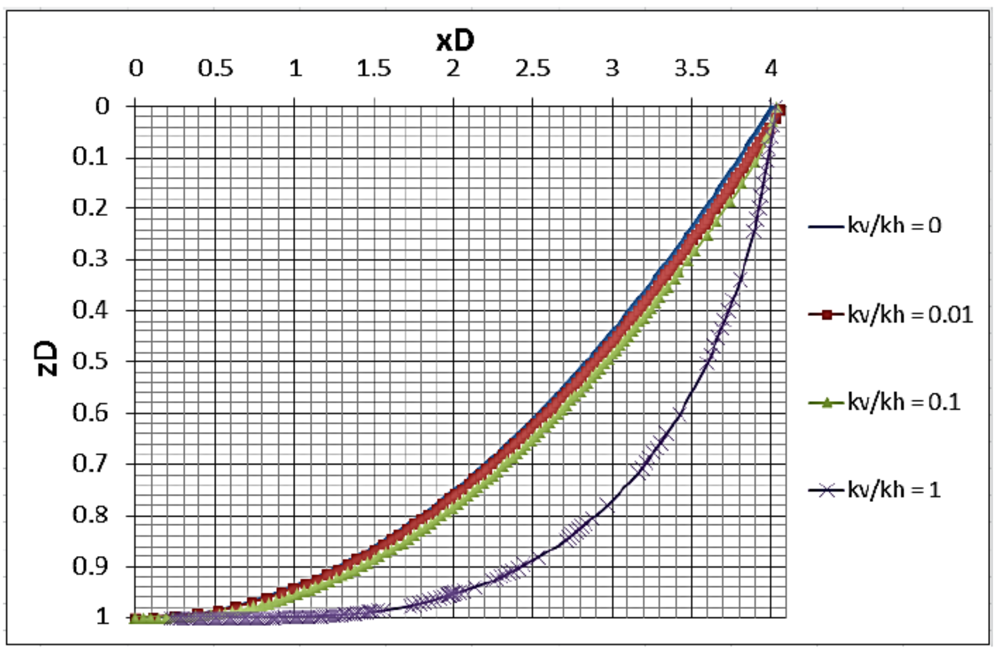


Figure 2.8: Comparison of Flood Fronts for Various Permeability Ratios (Shan and Rossen, 2004)

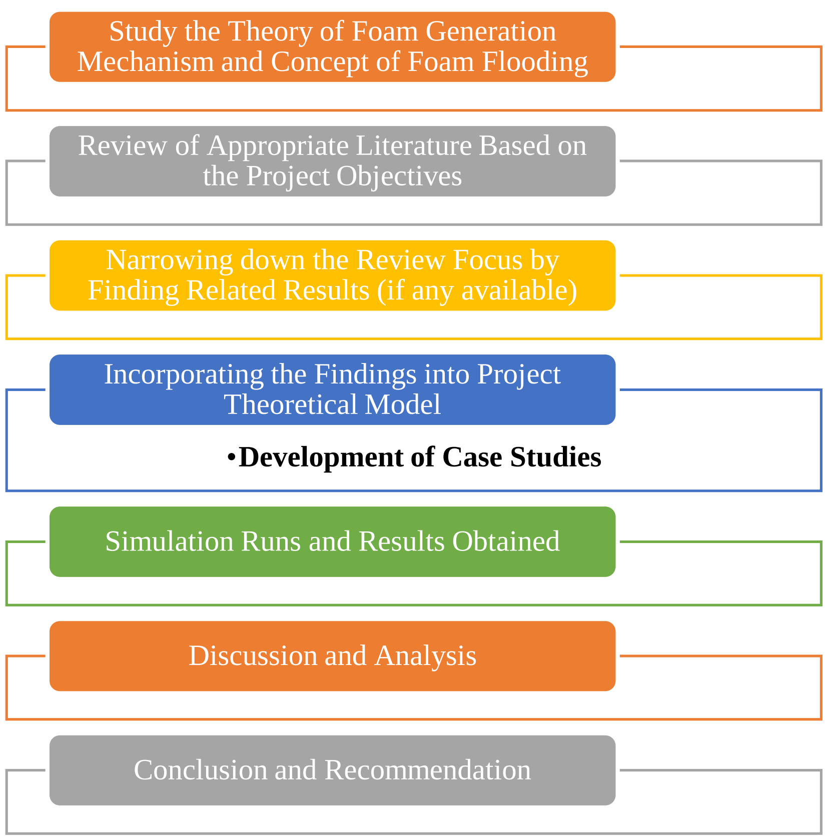
CHAPTER 3

METHODOLOGY

3.1 Research Methodology

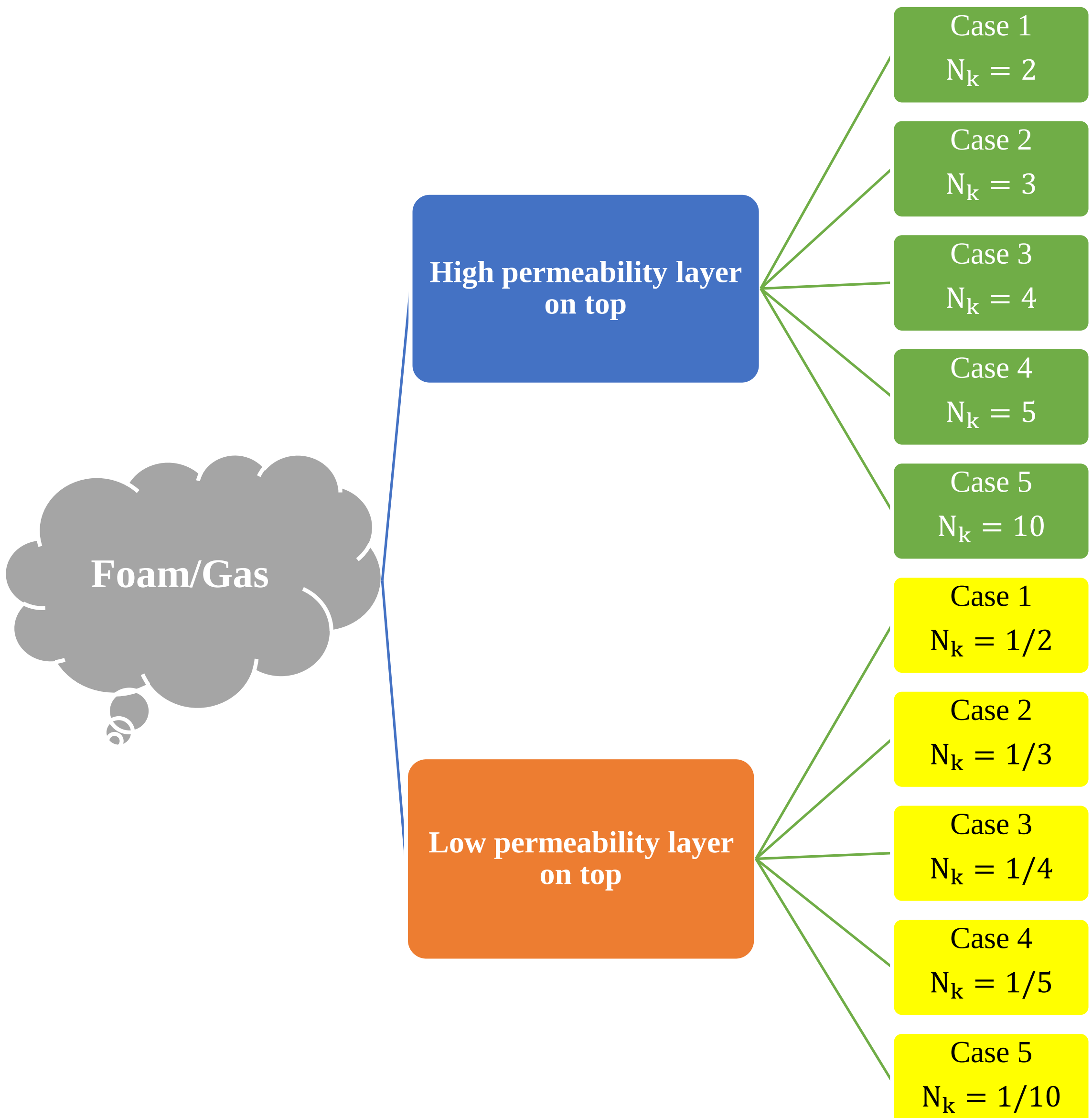
The research methodology serves as a guideline for the duration of twenty eight weeks provided for both parts of this project. The theoretical literature used in this paper involves basic fundamentals of foam generation in porous media and its applications in pilot and field scale projects. As a result, the most important emphasis of foam flooding in a heterogeneous reservoirs is taken into account with regard to recent research findings and results. The project flow is illustrated clearly in the next section.

3.2 Project Flow



3.3 Case Studies

The simulation runs were conducted for two configurations of vertical heterogeneity: first, the low permeable layer is on top of the high permeable layer. Secondly, the simulations runs are conducted for "vice versa" configuration. Note, that each configuration has five runs based on cases shown below respectively.



3.4 Gantt Chart

1. **Final Year Project I**

Event/Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Project title selection	■	■	■ ★											
Preliminary research work				■	■	■	■							
Extended proposal submission							■	■ ★						
Proposal Defense									■ ★					
Project Work Continues									■	■	■	■		
Submission of Interim Draft													■ ★	
Submission of Interim Report														■ ★

Table 3.1: Final Year Project I Gantt Chart

2. **Final Year Project II**

Event/Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Project work commencement	■	■	■	■	■	■	■							
Progress report submission							■ ★							
Pre-SEDEX/Poster Presentation								■	■ ★					
Final draft/Technical Paper submission									■	■	■	■ ★		
Final oral presentation/ VIVA													■	■ ★

Legend	
Deliverables	★
Progress	■

Table 3.2: Final Year Project II Gannt Chart

3.5 Reservoir Model and Foam Parameters

In this study, simulations were run in Eclipse E100, developed by Schlumberger. All reservoir sides are bounded by no-flow boundaries. There are one injection well and one production well that are placed diagonally, in a quarter portion of an inverted 5-spot injection pattern. The reservoir heterogeneity is represented by layers with various permeability. There are five high permeable layers, and five low permeability layers. Each layer has identical thickness, a homogeneous porous medium with identical properties in all Cartesian directions. For this study, firstly, the simulations are run when the high permeability layer is located on top of the low permeability layer. Secondly, the simulation studies are conducted when the low – permeability layer is on top of the high – permeable layer. This choice of compartmentalized reservoir is a compromise between various permeability layers as it was discussed in Chapter 2. The parameters of foam used are taken from published data, which is openly avail be for educational purposes. Detailed information is provided in APPENDIX I.

Assumptions

- No – flow boundaries
- Laminar flow (Darcy's law applied)
- Isothermal conditions
- Gravity forces not neglected
- Capillary forces are negligible
- Cross – flow allowed
- Zero skin (effect)

3.5.1 Reservoir Model and Reservoir Fluid Densities at Standard Conditions

RESERVOIR MODEL					
Properties/Cases	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Reservoir Dimensions	50x50x10				
Grid Size (ft)	100x100				
Porosity	0.3				
High k layer thickness, ft	20				
Low k layer thickness, ft	30				
$\mathbf{N_k}$ ratio	2:1 / 1:2	3:1 / 1:3	4:1 / 1:4	5:1 / 1:5	10:1 / 1:10
$\mathbf{k_x = k_y = k_z}$ (high k layer) (mD)	100	150	200	250	500
$\mathbf{k_x = k_y = k_z}$ (low k layer) (mD)	50	50	50	50	50
Surfactant solution (3 % wt) + continuous gas injection – Foam generation process	100,000 stb/ day - 91 days, 100,000 Mscf/day – 7020 days				
Gas flooding, surface injection rate	100,000 (Mscf/day) - 7111 days				

Table 3.3: Reservoir Model

Fluid densities at surface conditions($\frac{ft^3}{lb}$)		
Oil	Water	Dissolved Gas
49.1	64.79	0.06054

Table 3.4: Fluid Densities at Surface Conditions

3.5.2 Expected Outcome

With regard to analytical and experimental studies, the essence of foam generation in a porous medium was found to be crucial to recover additional oil from the reservoir. As this study seeks to investigate how foam flooding could be beneficial compared to conventional gas flooding processes, the application of foam is only viable for the model provided. The model represents an ideal cake-like layered porous medium, with alterations in permeability of each layer. Each layers is a homogeneous unit that has its respective horizontal permeability, whether low or high. Moreover, it is assumed that there exists vertical communication between layers and vertical permeability contrast is at least equal or greater the critical value of four. As it can observed from the figure below, the injected foam is capable of reducing the mobile gas by suppressing it vertically downward, thus delaying early gas breakthrough and improving the sweep efficiency.

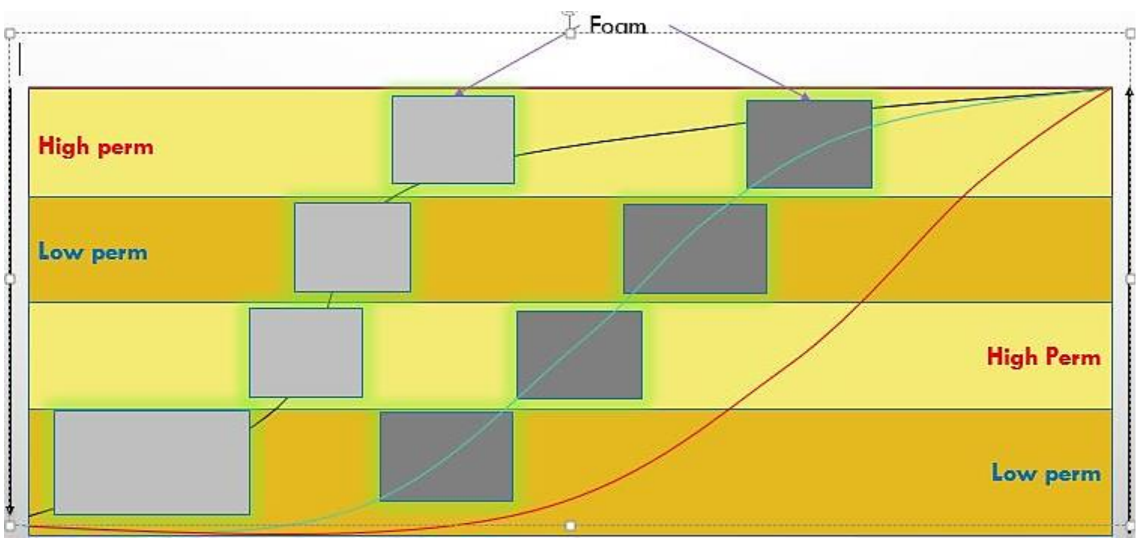


Figure 3.1: Expected Outcome of Foam Flow (study model)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Simulation Results and Discussion

The results were obtained from simulation runs using Eclipse E100. The simulations outcomes considered were Gas – Oil Ratio, Gas Mobility Reduction, and Oil Recovery Efficiency. There have been ten simulation runs in total for each configuration of layers – five for foam generation/gas flooding processes, and five for gas flooding processes. A comparison analysis was carried out based on the cases considered. All foam generation/gas flooding processes were compared to their counterparts – gas flooding processes for each cases separately and all together, depending on the outcome(s).

4.1.1 Foam Generation Effect on Gas – Oil Ratio and Gas Mobility Control

During gas injection processes, gas – oil ratio or GOR at the production well increases with time, due to early breakthrough of the gas and poor sweep conformance. Therefore, the objective of this section was to show if there was any impact of foam on gas – oil ratio and how much gas mobility was controlled by foam, where the results obtained were compared to sole gas injection into the respective cases. The figures below provide an illustrative comparison, where results obtained are provided for all cases considered in the project.

A. Low – permeability on top

Case 1: $N_k = 1:2$ (50 mD / 100 mD)

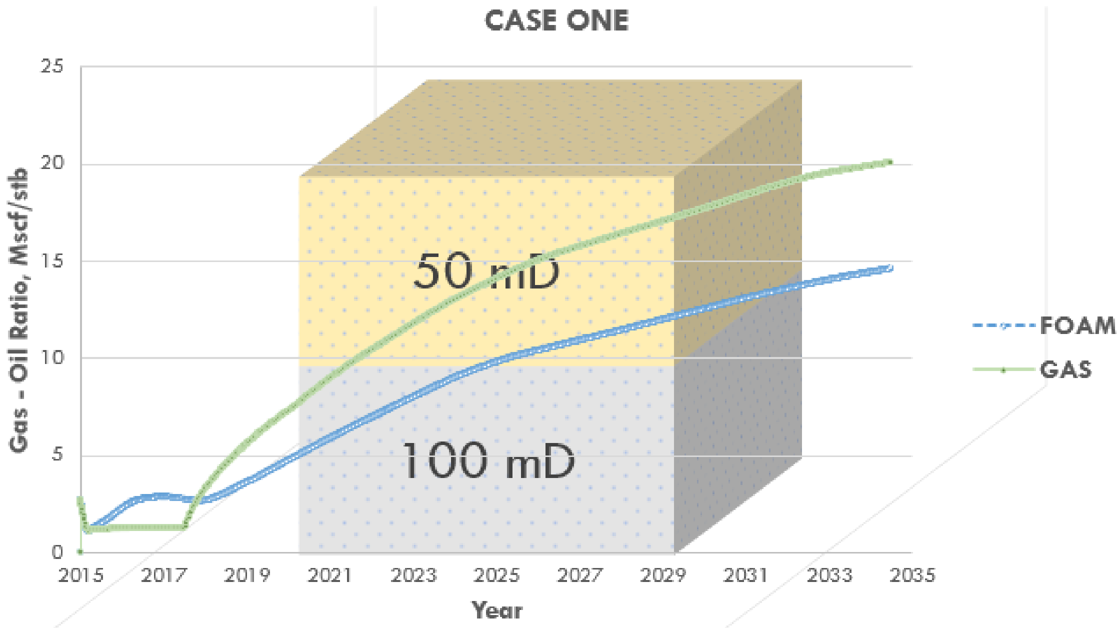


Figure 4.1: Gas - Oil Ratio: Case One (Low – permeability on Top)

Case 2: $N_k = 1:3$ (50 mD / 150 mD)

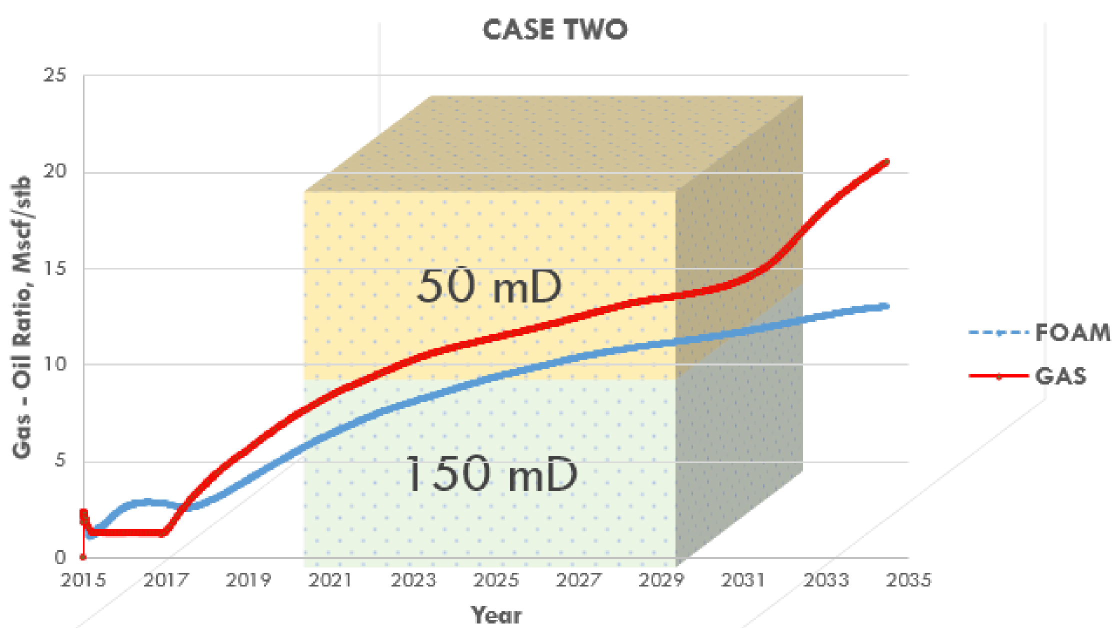


Figure 4.2: Gas - Oil Ratio: Case Two (Low – permeability on Top)

Case 3: $N_k = 1:4$ (50 mD / 200 mD)

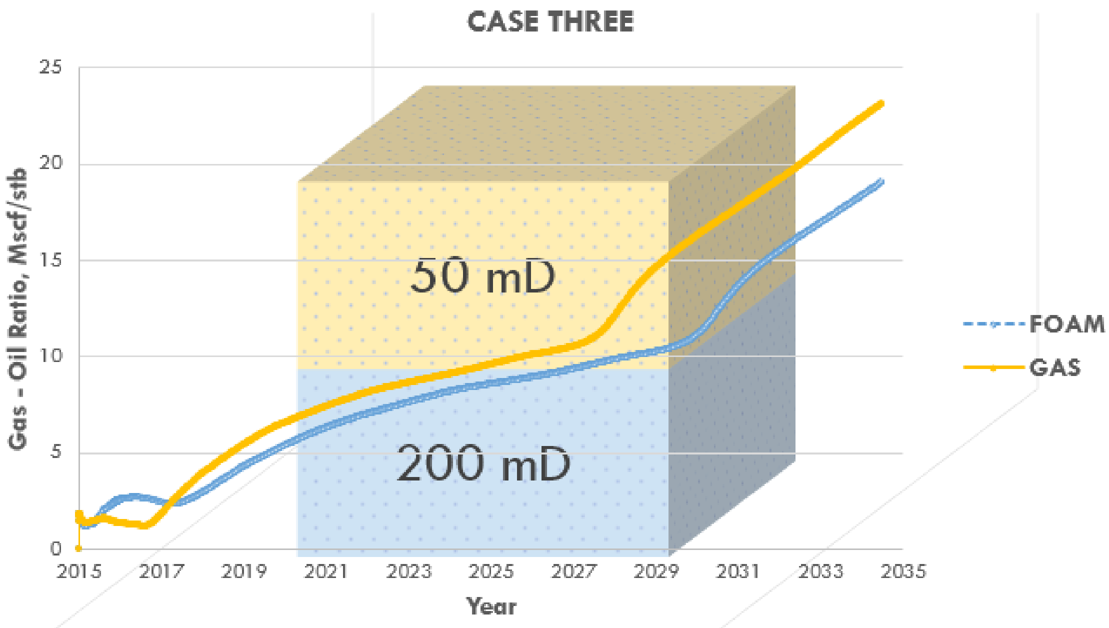


Figure 4.3: Gas - Oil Ratio: Case Three (Low – permeability on Top)

Case 4: $N_k = 1:5$ (50 mD / 250 mD)

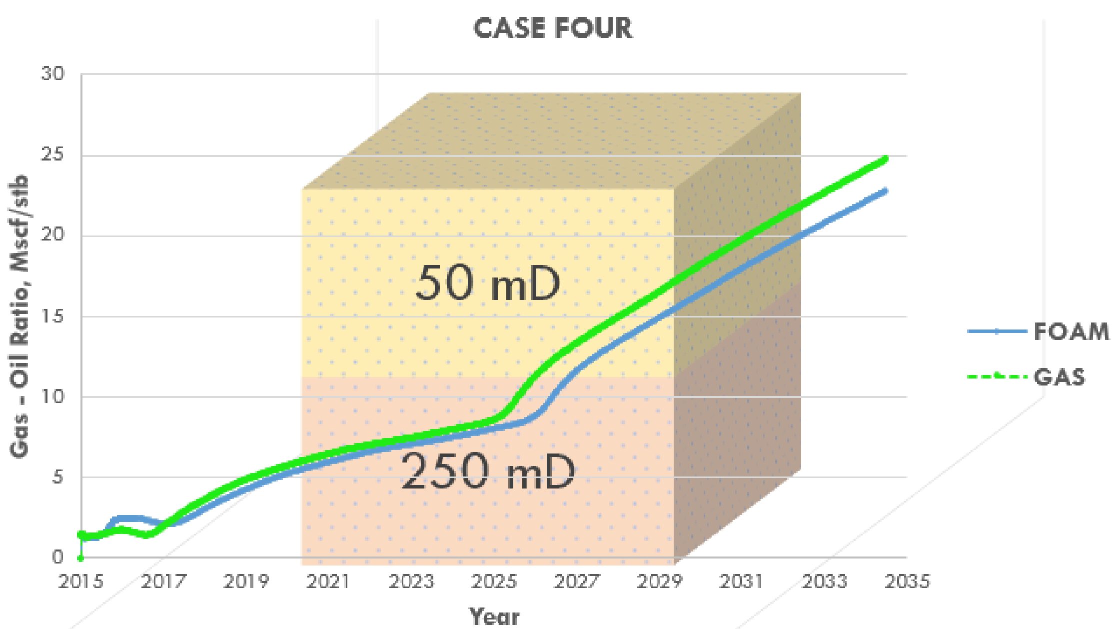


Figure 4.4: Gas - Oil Ratio: Case Four (Low – permeability on Top)

Case 5: $N_k = 1:10\ (50\ \text{mD}\ /\ 500\ \text{mD})$

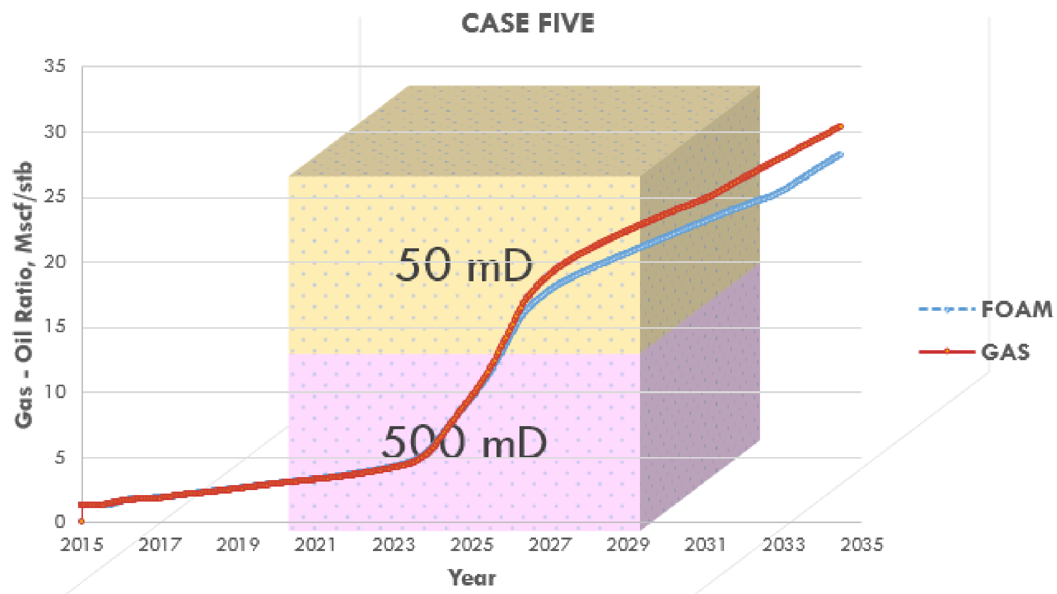


Figure 4.5: Gas - Oil Ratio: Case Five (Low – permeability on Top)

Gas Mobility Control For All Cases

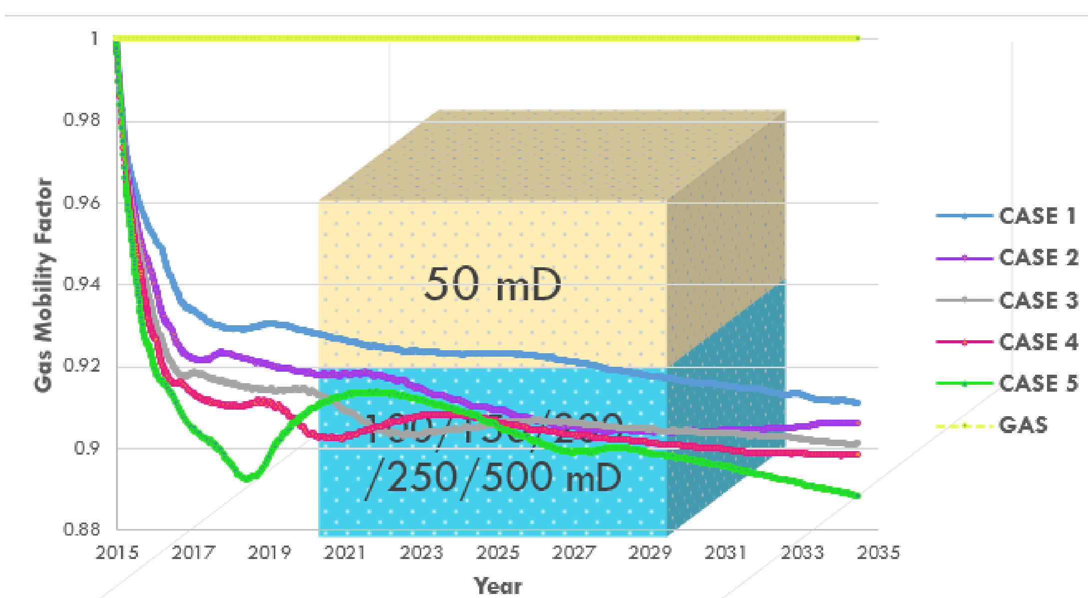


Figure 4.6: Gas Mobility Control: All Cases (Low – permeability on Top)

Discussion

Figures 4.1 to 4.5 display effects of foam generation process and its gas counterpart for each case respectively. As it is shown there, the behaviors observed were quite different as they had various tendensies. Firstly, it must be noted that the surfactant solution was injected into the upper layer, that is low – permeable one. Certainly, it was not expected to have surfactant solution propagated deep into the formation because of low permeablity (50 mD). Due to existence of cross – flow, the surfactant solution's presence was also encountered, at least partly, in high – permeable (bottom) layers. Thus, it can be said that we have had the surfact solution throughout entire formation. Secondly, the gas injections processes were performed into the bottom, higher permeable, zone. Consequently, the amount of gas injected in the high – permeable zone was greater than in the upper zone with surfactant solution.

The mentioned figures have one point in common, that is pretty clear when the injected gas had a breakthrough with respect to the case shown. The greater high – permeable layer was, the shorter was the time of gas breakthrough. An interesting set of results were observed when the foam was generated in the same porous media. Generally, it can be seen that in all cases foam generation had not had significant impact in the early years of injection processes, even though the mobility of the gas was lower and lower as the permeability of the lower zone increased.

Overall, the gas mobility reduction was relatively insignificant as approximately 10% was observed on average in all cases. The explaination of foam failure to control gas – oil ratio is quite simple. As it is said above, the propagation of surfactan solution in the upper zone was almost same in all cases, however the permeability of the lower zone had an incremental tendency from case to case. Such a tendency resulted in bypassing and little or less interaction between layers when the gas was injected, thus the gas was more mobile with increasing permeability. This implies that little time was allowed to generate foam even though the permeability contrast between layers was meet. Figure 4.5 clearly proves the point, that there was almost no interaction between surfactand solution and gas, or even if there was any contact, it only resulted in a very weak foam formulation which was not able to control the gas front at all.

B. High – permeability on top

Case 1: $N_k = 2:1$ (100 mD / 50 mD)

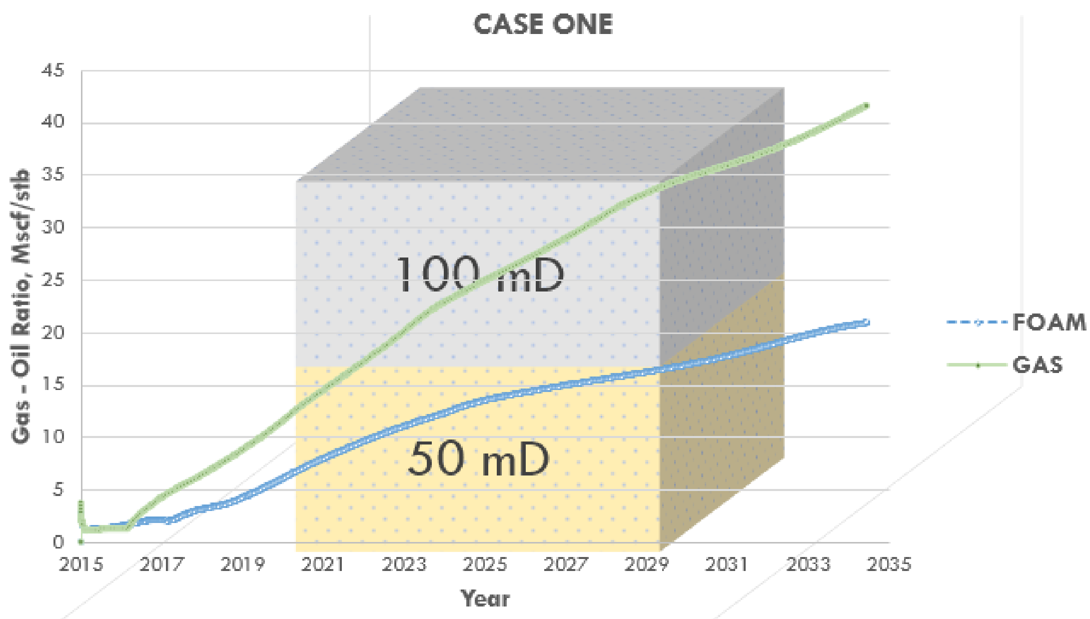


Figure 4.7: Gas - Oil Ratio: Case One (High – permeability on Top)

Case 2: $N_k = 3:1$ (150 mD / 50 mD)

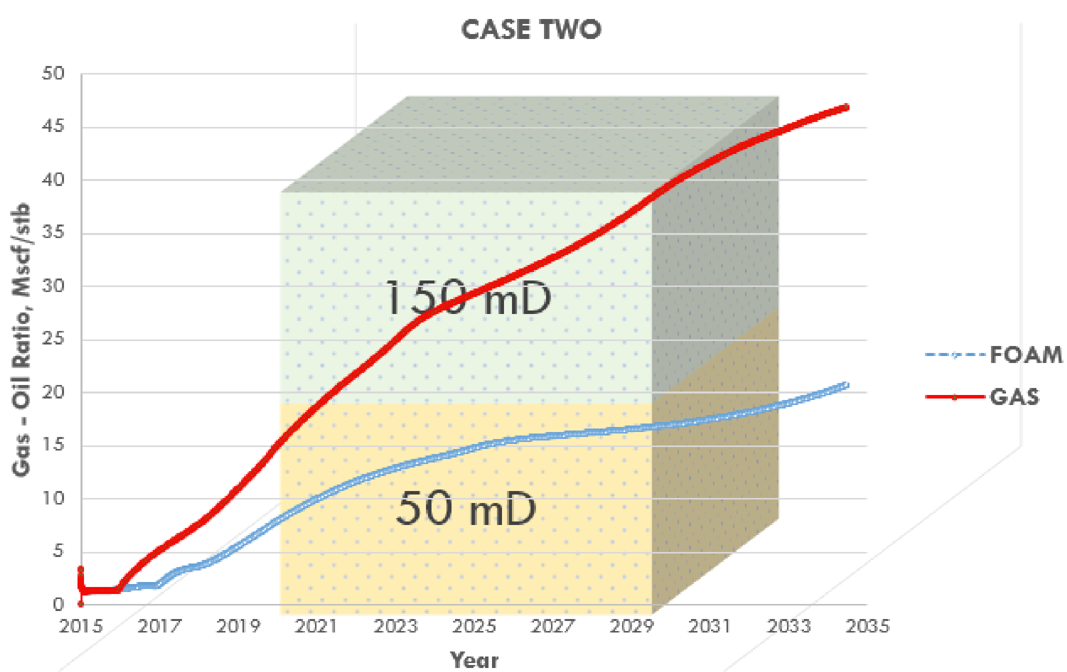


Figure 4.8: Gas - Oil Ratio: Case Two (High – permeability on Top)

Case 3: $N_k = 4:1$ (200 mD / 50 mD)

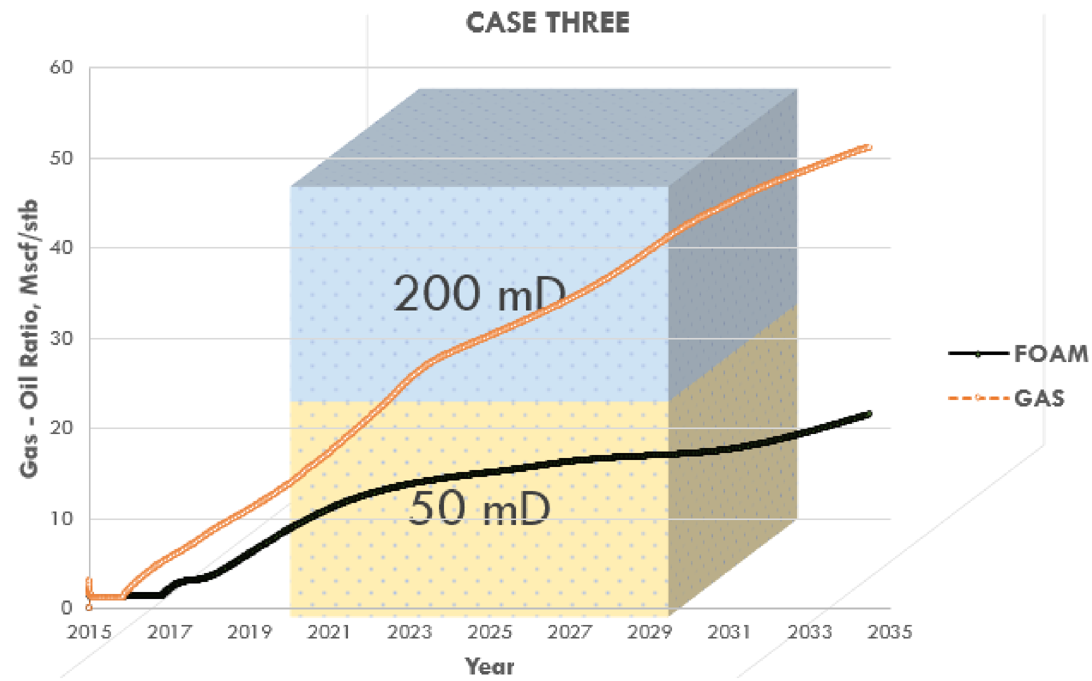


Figure 4.9: Gas - Oil Ratio: Case Three (High – permeability on Top)

Case 4: $N_k = 5:1$ (250 mD / 50 mD)

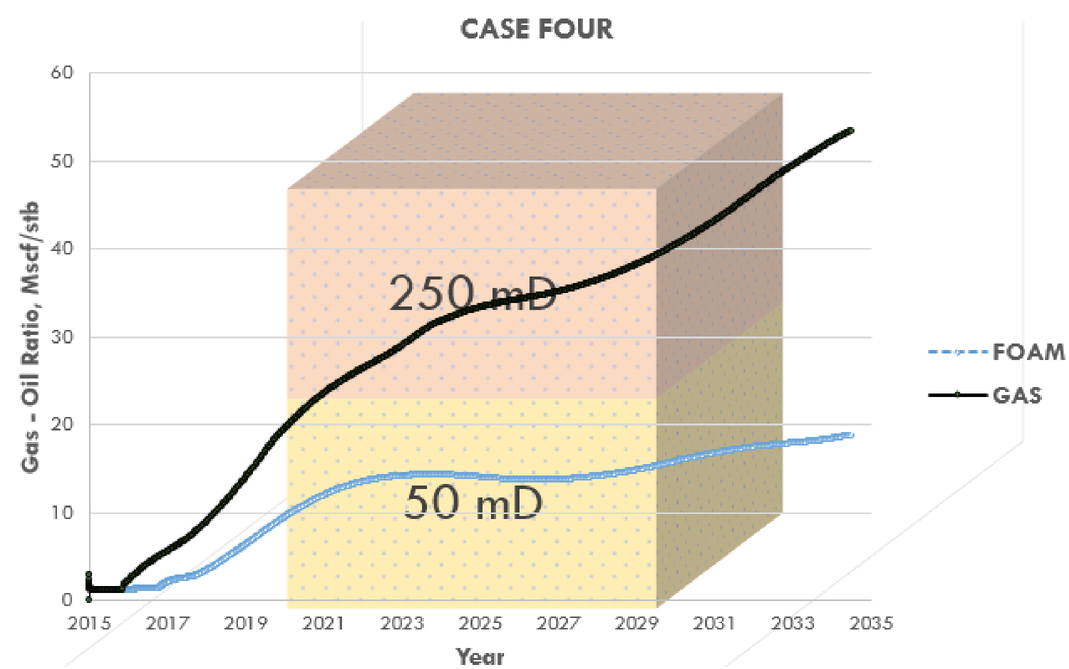


Figure 4.10: Gas - Oil Ratio: Case Four (High – permeability on Top)

Case 5: $N_k = 10:1$ (500 mD / 50 mD)

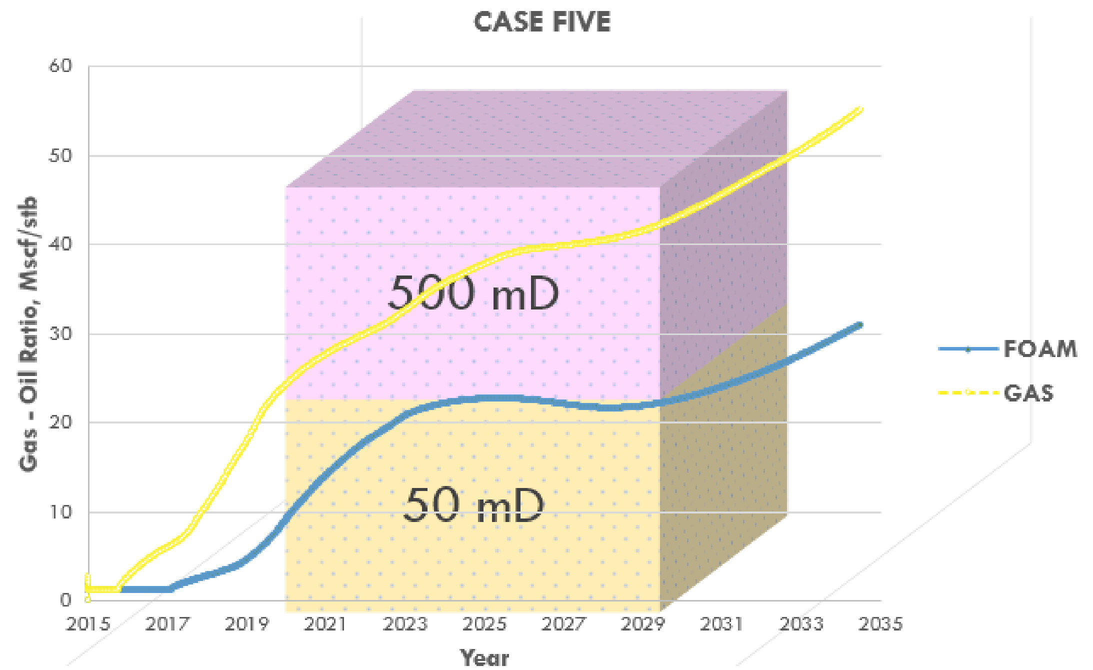


Figure 4.11: Gas - Oil Ratio: Case Five (High – permeability on Top)

Gas Mobility Control For All Cases

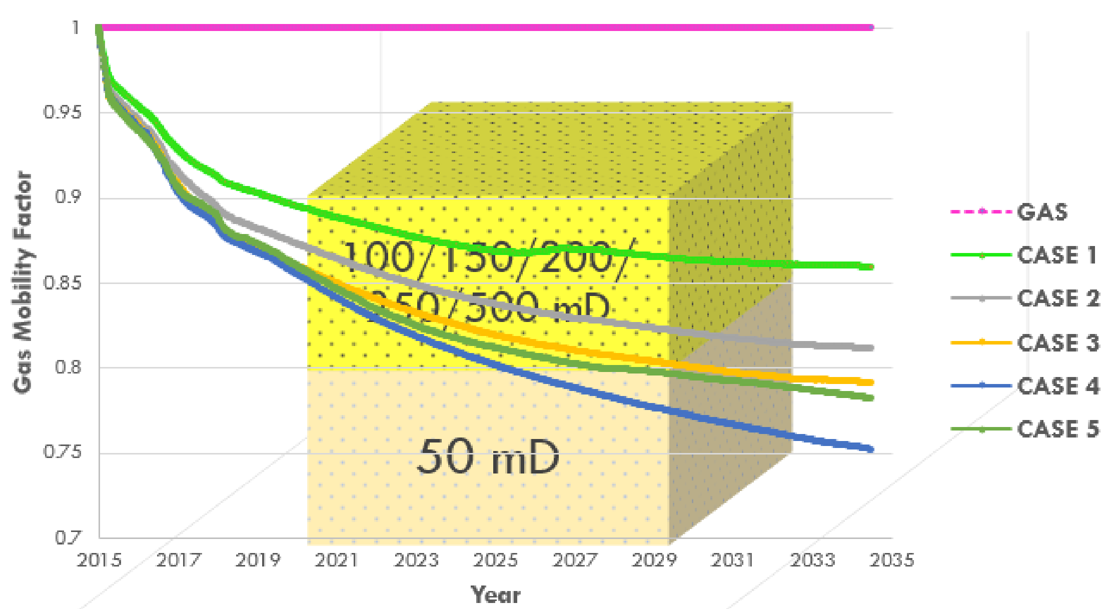


Figure 4.12: Gas Mobility Control: All Cases (High – permeability on Top)

Discussion

Figures 4.7 to 4.11 display effects of foam generation process and its gas counterpart for each case respectively. As it is shown there, the behaviors of the injected gas are quite similar in all five cases. Firstly, it must be reminded that the surfactant solution was injected in the upper layer, that is high – permeable one, therefore it was expected to have deeper surfactant solution propagation with inreasing permeability of the upper layer. By contrast, the low permeable layer remained same throughout the experiment (50 mD). As cross – flow existed, the surfactant solution's presence was obvious in high – permeable layers, and partly distributed in the lower zone too. Thus, it can be said that we have had the surfact solution throughout entire formation. Secondly, the gas injection processes were performed at the bottom, low permeable, zone. There are some common points in all gas injection processes, such as that the gas breakthrough occurred at nearly same time after the injection had started. Another common point is that in all cases, the foam generation was quite useful and successful at controlling the gas – oil ratio, resulting in gas breakthough delays.

A type of foam generated in – situ can be supported with help of Figure 4.12, where the figure shows how much was the gas mobility reduced due to foam. It suggests that most probably the foam generated was continuous in Cases One and Two, although the mobility reduction curves indicates clear differences. In Case Three, the required permeability ratio was met, and it even slightly exceeded in Case Four which indeed is supported by their respective gas mobility reduction curves. Its implication is that more strong foam was generated by the snap – off mechanism, and more bubbles were transported into the high – permeable formation. However, in the case of very abrupt permeablity contrast (Case Five), the gas mobility curves is very near or have almost same output, even though it is obvious that definitely strong foam was generated, and it was generated by the snap – off mechanism. Thus, it can be concluded that as long as the required permeability ratio is met, strong foam would cetainly be generated by the snap – off mechanism, however it would be relatively more mobile in high permeability zones because of the foam bubbles would be transported deeper into the formation.

4.1.2 Foam Flow Effect on Oil Recovery Efficiency

A. Low – permeability on top

Case 1: $N_k = 1:2$ (50 mD / 100 mD)

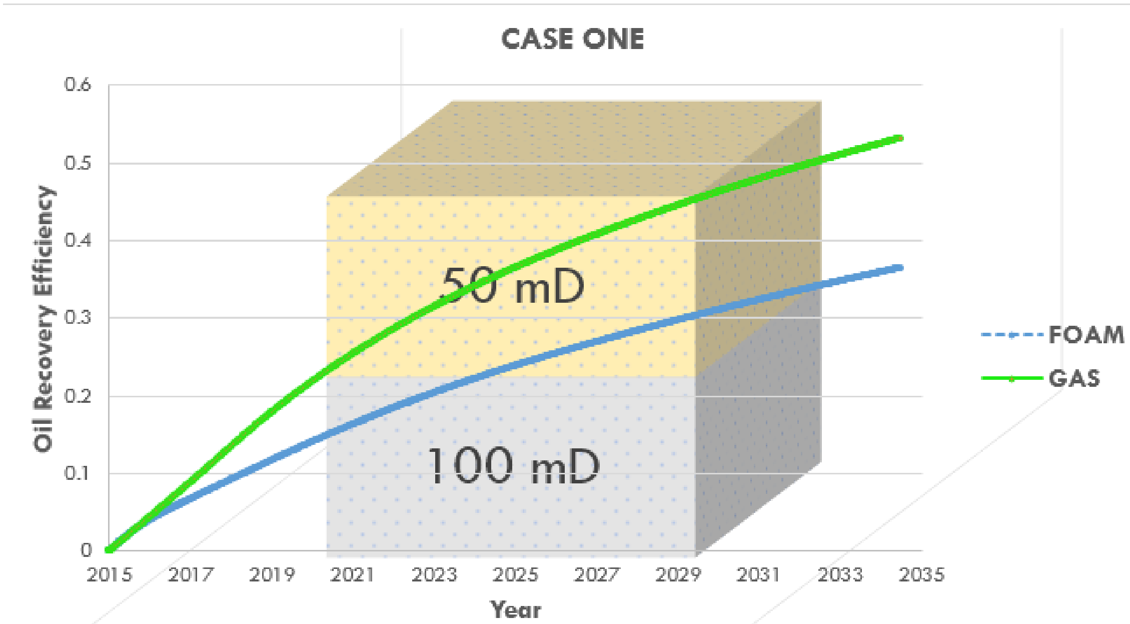


Figure 4.13: Oil Recovery Efficiency: Case One (Low – permeability on Top)

Case 2: $N_k = 1:3$ (50 mD / 150 mD)

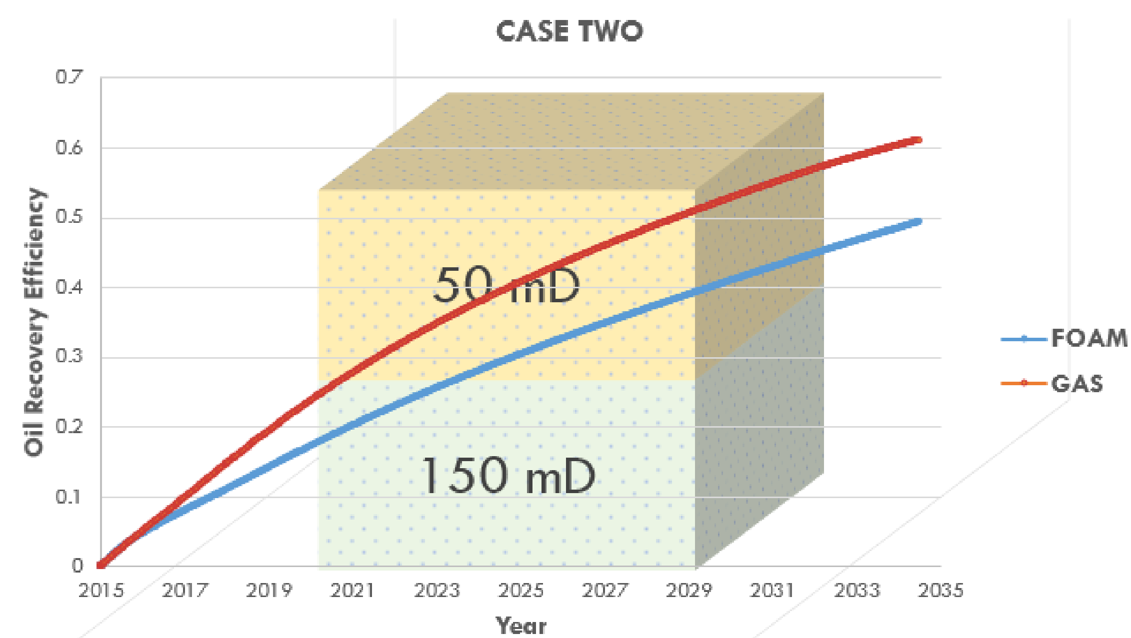


Figure 4.14: Oil Recovery Efficiency: Case Two (Low – permeability on Top)

Case 3: $N_k = 1:4$ (50 mD / 200 mD)

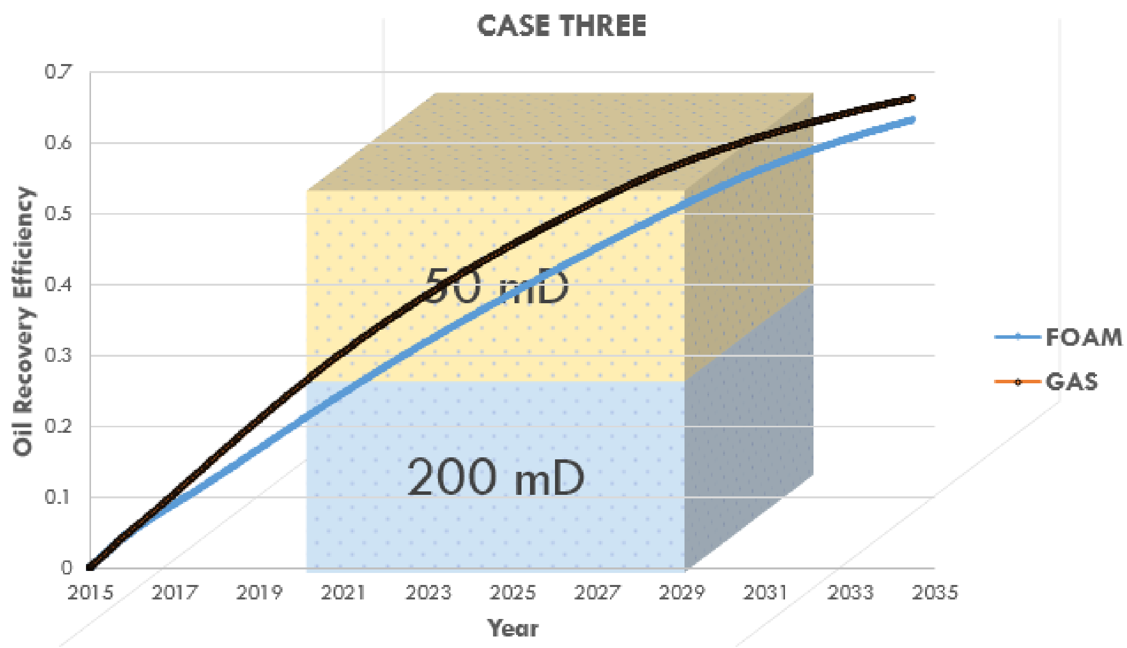


Figure 4.15: Oil Recovery Efficiency: Case Three (Low – permeability on Top)

Case 4: $N_k = 1:5$ (50 mD / 250 mD)

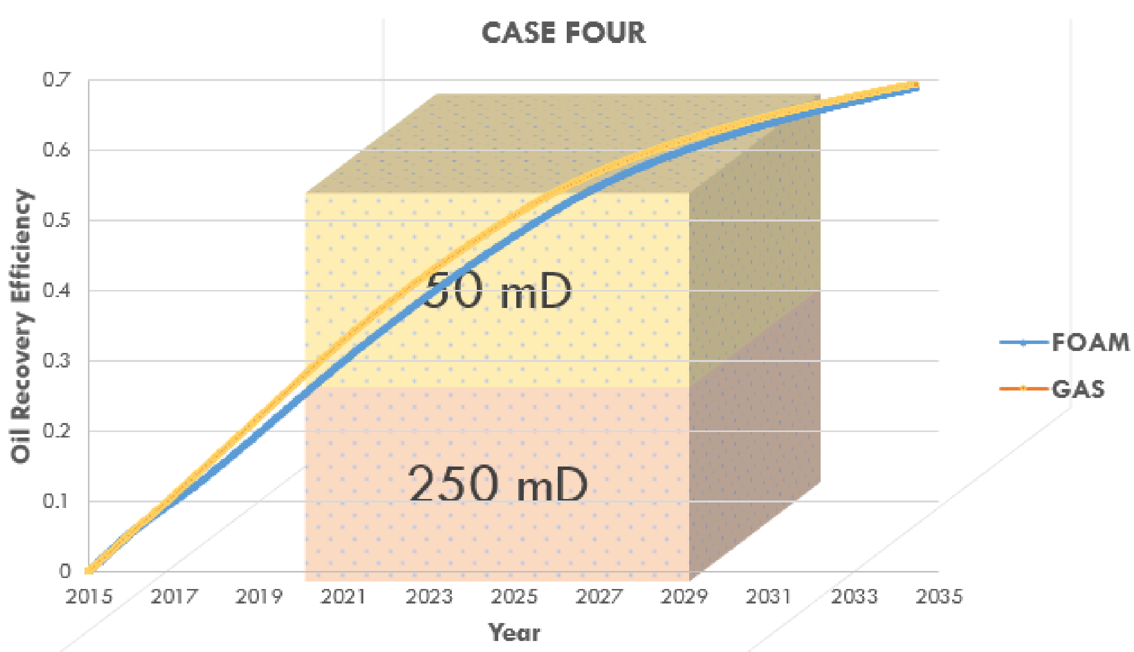


Figure 4.16: Oil Recovery Efficiency: Case Four (Low – permeability on Top)

Case 5: $N_k = 1:10\ (50\ mD\ /\ 500\ mD)$

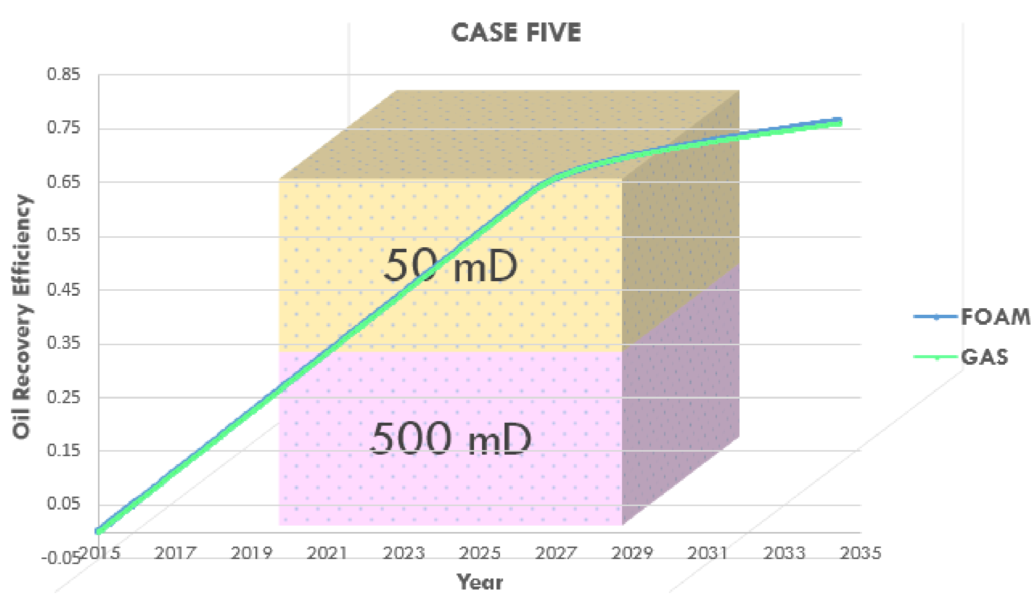


Figure 4.17: Oil Recovery Efficiency: Case Five (Low – permeability on Top)

Discussion

This section of the chapter discusses impact of foam generation on oil recovery efficiency with respect to its gas counterpart. With regard to section 4.1.1 A, it can be said that there is a definite close connection between gas – oil ratio and oil recovery efficiency values. First of all, let's recall what sort of output was obtained in Cases One, Two and Three. As it has been discussed earlier, foam had been generated in relatively small quantities when the ratio of permeability between layers was not that large enough as in Cases Four and Five. In first three cases, gas – oil ratio was more or less successfully controlled, whereas in the last two cases the surfactant solution was almost bypassed. The result of foam generation in the first three cases had a detrimental effect on the ultimate oil recovery, because even there was foam generated, it kept the injected gas trapped or impeded from flowing. Nonetheless, with permeability increase in the lower zone, the gap between foam and gas oil recovery curves was getting closer. Furthermore, as it can be seen from Cases Four and Five, both gas and foam processes have nearly identical output in terms of recovering oil. The implication of such outcomes is that there was no foam or very weak foam generated, and the injected gas in the lower high permeable zone had similar or even same paths in both gas and foam processes.

B. High – permeability on top

Case 1: $N_k = 2:1$ (100 mD / 50 mD)

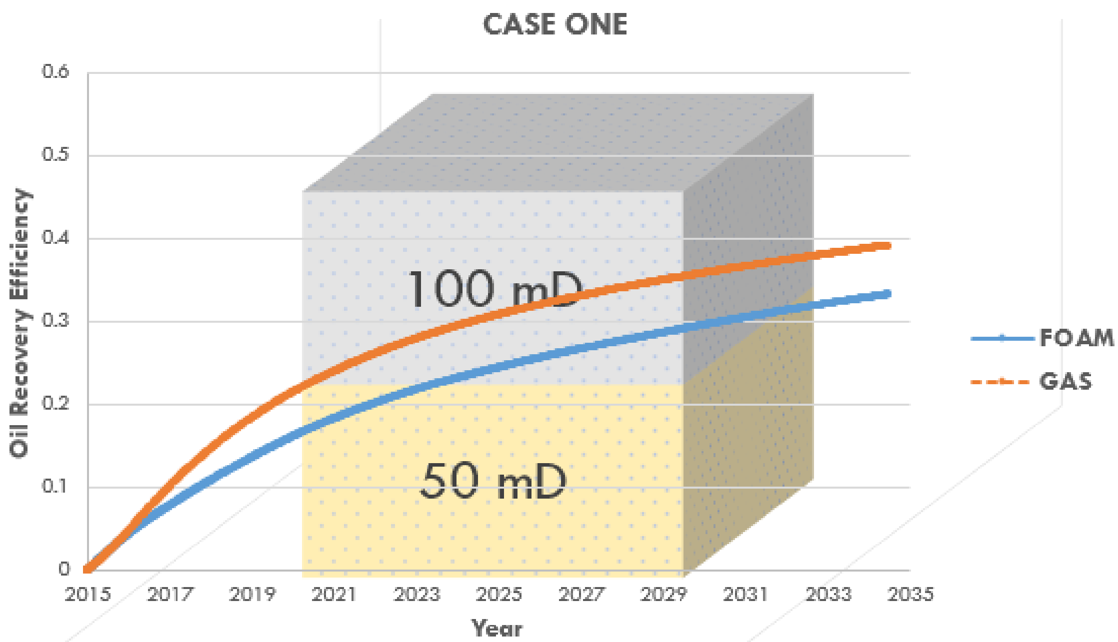


Figure 4.18: Oil Recovery Efficiency: Case One (High – permeability on Top)

Case 2: $N_k = 3:1$ (150 mD / 50 mD)

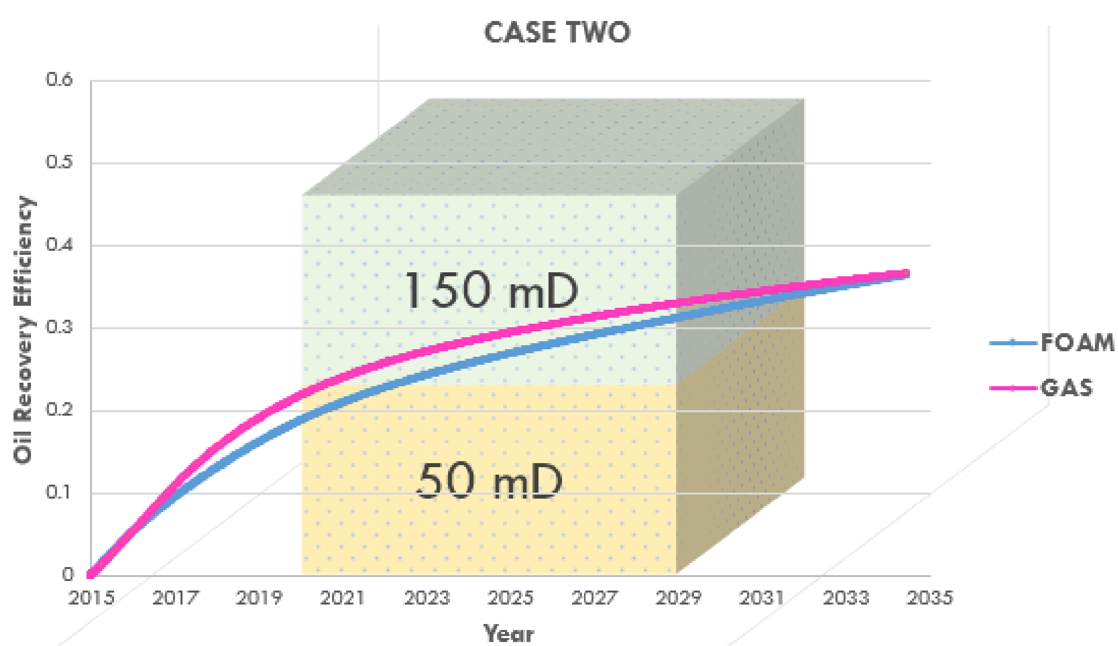


Figure 4.19: Oil Recovery Efficiency: Case Two (High – permeability on Top)

Case 3: $N_k = 4:1$ (200 mD / 50 mD)

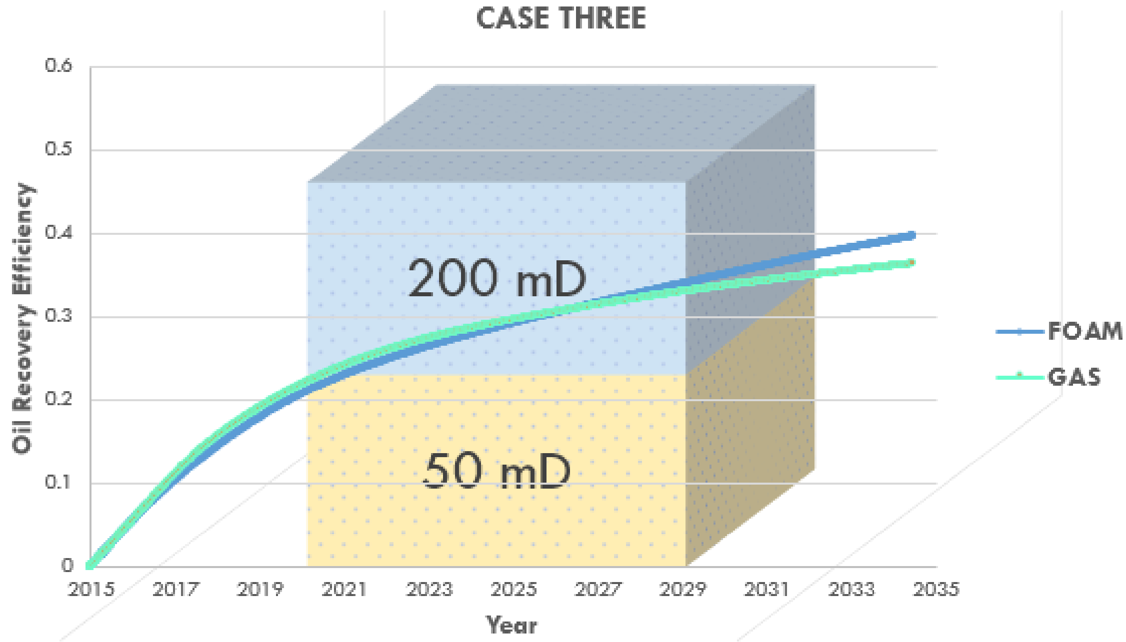


Figure 4.20: Oil Recovery Efficiency: Case Three (High – permeability on Top)

Case 4: $N_k = 5:1$ (250 mD / 50 mD)

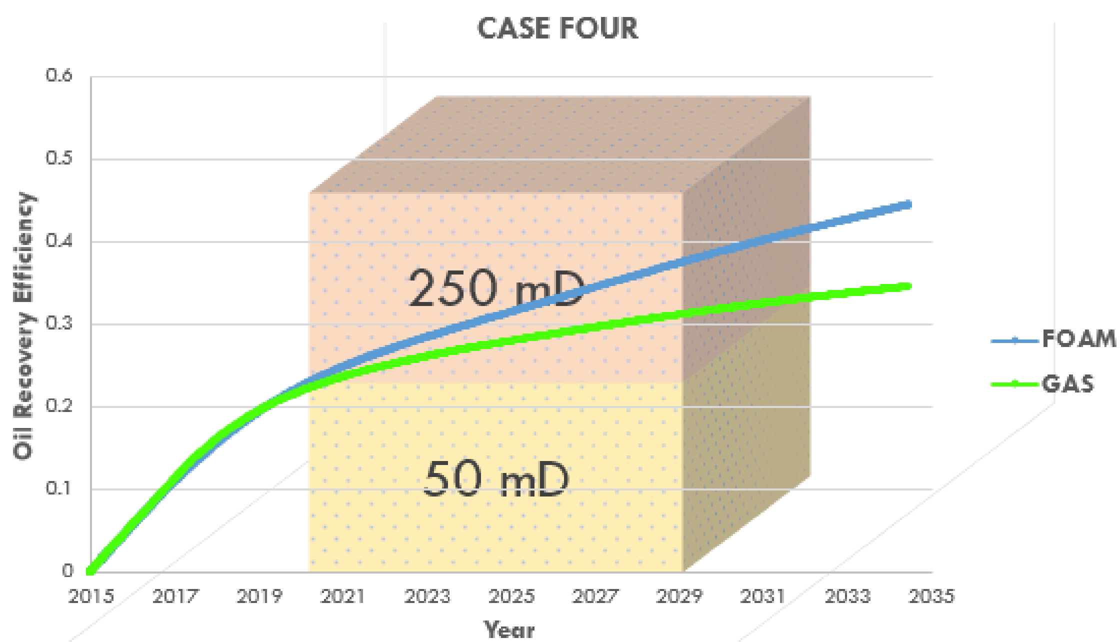


Figure 4.21: Oil Recovery Efficiency: Case Four (High – permeability on Top)

Case 5: $N_k = 10:1\ (500\ mD\ /\ 50\ mD)$

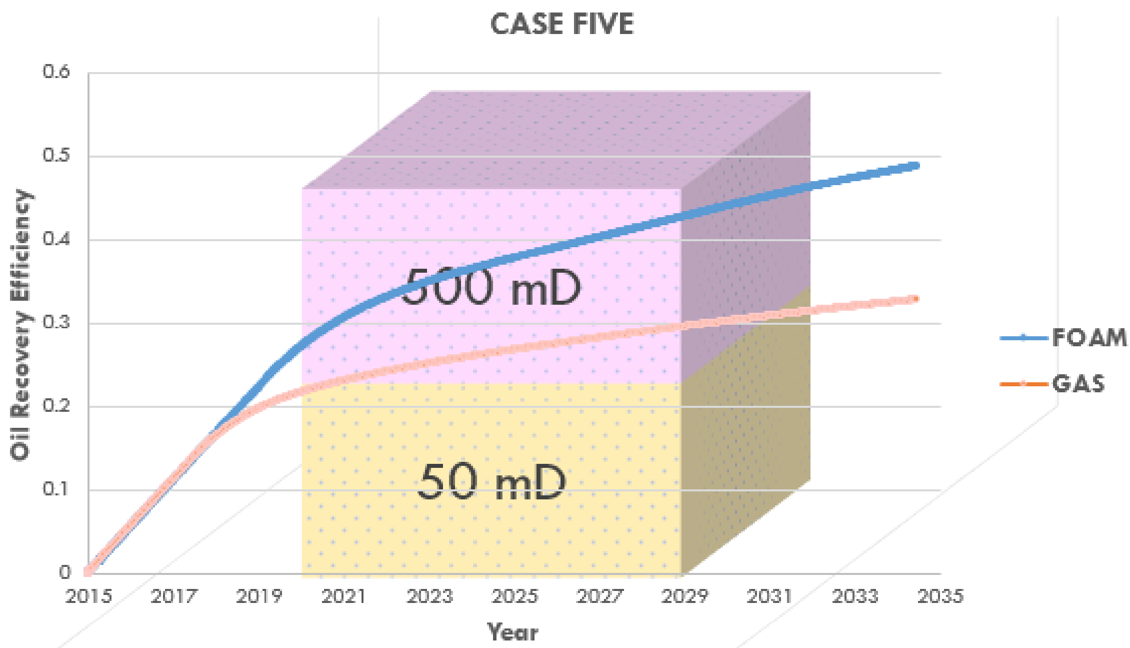


Figure 4.22: Oil Recovery Efficiency: Case Five (High – permeability on Top)

Discussion

This section covers a discussion on how foam generation have been beneficial to recover oil with regard to its gas counterpart, where the high – permeable layer was on top of the low – permeable layer, which remained same in all cases. From Figures 4.18 and 4.19 it can be seen, that the oil recovery with foam generated was either less or almost same as compared to the respective gas injection processes. It is an indication of continuous or weak foam generation, which indeed was not able to divert the gas flood front, but only slowed it down. The justification of that can be found in Section 4.1.1 B, Gas – Oil Ratio plots clearly showed that in all cases foam was successful to reduce gas – oil ratio values and delay gas breakthrough. By contrast, oil recovery efficiency increased with increased permeability ratio. Once the ratio satisfied the snap – off foam generation requirement, it was able to control gas more efficiently and effectively, thus recover more oil. Subsequently, a slight increase over the required value (Case Four) also proved the point, that the higher the ratio was, the more oil was produced. Ultimately, at very abrupt permeability ratio (Case Five), much more oil was recovered as compared to gas, because more foam (bubbles) would be transported deeper into the formation.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study illustrates a number of cases, where the impact of foam generation in gas injection processes has been examined and compared to their conservative gas injection counterparts respectively. The results obtained were discussed for a scenario where the low – permeable layer is on top of the formation, and situation where the high – permeable layer was on top of the low – permeable one.

When the top layer is low – permeable, it is concluded:

- → Gas – oil ratio was well controlled by foam generation process when the permeability contrast between layers did not meet the snap – off generation mechanism value of four. Despite of this result, the gas – oil ratio was nearly same or quite similar with results exhibited by the gas injection process. The mobility of gas was not low enough to control the gas injection front in all cases in general
- → It can be concluded, that foam generated was not strong at all, and thus it was continuous. In some cases, where the permeability contrast ratio was large enough, it is suspected that the injected gas bypassed pores filled with surfactant solution, thereby foam had no control over gas flood front
- → And most importantly, the generated foam failed to contribute to ultimate oil recovery at low permeability ratio values, whereas it merely executed same results just as a conventional sole gas injection at higher permeability contrast ratio values

When the top layer is high – permeable, it is concluded:

- → In all cases shown, generated foam showed promising results at controlling the gas – oil ratio regardless whether a strong or weak foam was generated. It was successful at delaying gas breakthroughs. The mobility of injected gases getting lower as the permeability contrast ratio was getting higher. Nonetheless, in case of a very abrupt contrast ratio, the gas was less mobile, although it almost same as in Case Three
- → The results obtained strongly suggest that with increase in permeability contrast, more and more foam bubbles could distributed deeper into formation, and the mechanism of generation was definitely the snap – off one. This statement is greatly supported by points made above
- → And the impact of foam generation varied from case to case. This implies that the generation of foam exhibited same results as its gas colleague, and even it was detrimental when the permeability ratio the least. But, as the permeability contrast met the required value of four, and even greater, the impact of foam generation was highly beneficial at recovering more oil

Foam generation is a complex process that is governed by many factors. Firstly, the application of foam in this project is limited to the assumptions made. Secondly, with respect to limitations and timeframe provided for this study, the study objectives have been successfully accomplished. As it had been observed and discussed in the previous chapter, the simulation runs have shown that generation of foam could be either beneficial than gas injection or not for various configurations of vertical heterogeneity. Therefore, a great care and consideration must be taken prior to its application is executed in real field studies.

5.2 Recommendations

As this project has fulfilled its objectives, it yet needs further improvements and modifications, thus the recommendations are as follows:

- → Conduct laboratory works with sand-packs with the same properties such as permeability and porosity, where foam parameters used would fit this model only
- → Include capillary pressure effect – to make it more realistically applicable
- → To maintain same volumetric size of the reservoir, but increase the number of grid blocks in all three directions – grid refinement. This modification would help analyze the impact of crossflow through vertical heterogeneity more accurately

REFERENCES

1. Bond, D.C., Holbrook , C.C.: "Gas Drive Oil Recovery Process", U.S. Patent No. 2,866,507 (December 1958)

2. Chaouche, M., Rakotomalala, N., Salin, D., Xu, B., and Yortsos, Y.C., *"Capillary Effects in Heterogeneous Porous Media: Experiments, Pore Network Simulations, and Continuum Modeling"* paper SPE 26658 presented at the 68th SPE Annual Technical Conference and Exhibition, Houston, Texas, 1993

3. Falls, A. H., Hirasaki, G. J., Patzek, T. W., Gauglitz, P. A., Miller, D.D., and Ratulowski, J: *"Development of a Mechanistic Foam Simulator: The Population Balance and Generation by Snap-Off,"* SPERE (Aug. 1988) 884-892.

4. Hirasaki, G.J. *"The steam-foam process," JPT,* May1989, 449-456

5. Renkema, W.J., Rossen, W.R.: *"Success of SAG Foam Processes in Heterogeneous Reservoirs"*, paper SPE 110408, presented at the 2007 SPE Annual Techical Conference and Exhibition, Anaheim, California, 11-14 November 2007

6. Rossen, W.R. 1996, "Foams in Enhanced Oil Recovery," in R.K. Prud'homme and S. Khan (eds) *Foams: Theory, Measurements and Applications*, Marcel Dekker, New York City

7. Rossen, W.R. 1999, *"Foam Generation at Layer Boundaries in Porous Media," SPE Journal* 4 (4)

8. Shan, D., Rossen, W.R.: *"Optimal Injection Strategies for Foam in IOR",* paper SPE 75180, presented the 13th SPE/DOE Symposium in Improved Oil Recovery, Tulsa, Oklahoma, 13-17 April 2002

9. Schlumberger, 2012 : "ECLIPSE Reference and Technical Description Manuals"

10. Tanzil, D., Hirasaki, G.J., and Miller, C.A.,: *"Mobility of Foam in Heterogenous Media: Flow Parallel and Perpendicular to Stratification,"* paper SPE 63228 presented at the 2000 SPE Annual Technical Conference and Exhibition, Dallas, Texas, 1-4 October, 2000

11. Tanzil, D. 2001, *Foam Generation at Layer Boundaries in Porous Media*, Ph.D. Thesis, Rice University, United States

12. Van Lingen, P.P. 1998, *Qualification and Reduction of Capillary Entrapment in Cross-Laminated Oil Reservoirs,* Ph.D. Thesis, Delft University of Technology, The Netherlands

APPENDICES

APPENDIX I

Foam Model

1. Foam carrier – Water (function)
2. Gas mobility reduction dependence upon foam surfactant concentration

Reference foam surfactant concentration above which a strong foam can form, lb/stb	Exponent controlling the steepness in the change of mobility reduction due to surfactant concentration
0.0035	2

3. Specification of foam – rock properties

Adsorption index to be used for this rock type	Mass density of this rock type at reservoir conditions, lb/rb
1	930

4. Surfactant adsorption onto the rock surface

Local foam concentration in the solution surrounding the rock, lb/Mscf	Corresponding saturated concentration of foam adsorbed by the rock formation, lb/lb
0	0
3.5E-6	0.000000
3.5E-5	0.0000010
3.5E-4	0.0000040
0.0035	0.0000250
0.0123	0.0000480
0.035	0.0000480
0.35	0.0000480
3.5	0.0000480

5. Foam mobility reduction – Functional dependence upon capillary number

Reference capillary number, N_c	Exponent controlling the steepness in the change of mobility according to the ratio of reference to calculated capillary numbers
7.84 E-8	1

6. Gas – water surface tension Vs Foam surfactant concentration

Surfactant concentration, lb/stb	Gas – water surface tension, lbf/in
3.5E-4	2.855E-4
0.0035	1.370E-4
0.0123	5.139E-5
0.035	5.139E-5
0.35	5.139E-5

7. Reference mobility reduction factor

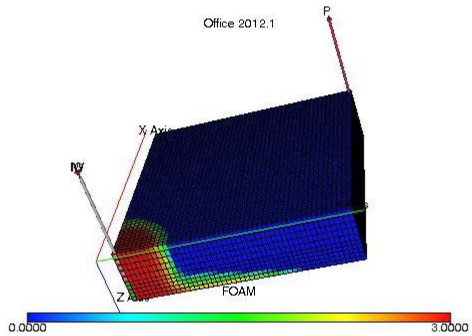
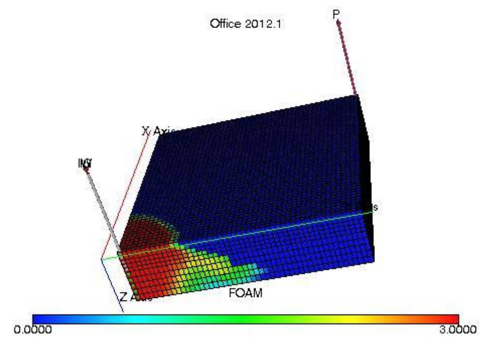
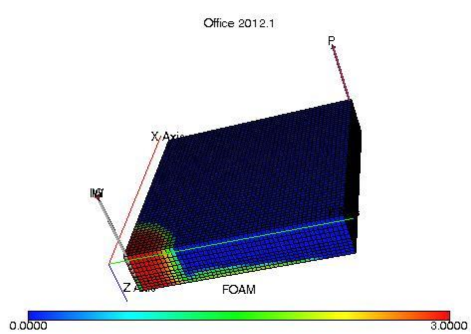
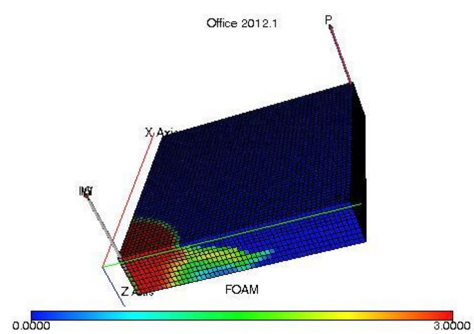
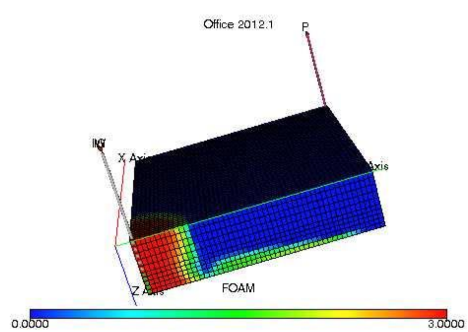
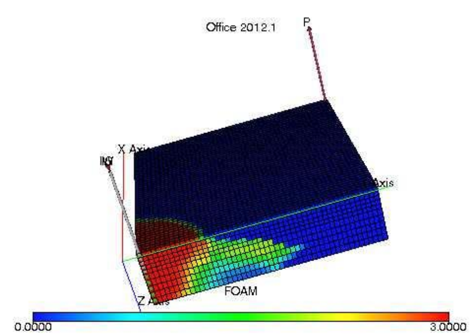
   FOAMFRM = 50

8. Gas mobility reduction factor dependence upon water saturation and oil saturation

Function \ Parameter	Limiting water saturation below which the foam ceases to be effective	Weighting factor which controls the sharpness in the change of mobility
FOAMFSW	0.3	2
FOAMFSO	0.7	1

APPENDIX II

Foam Fronts after the Injection Period

Low – permeability on Top	**High – permeability on Top**
Case One	
$N_k = 1:2$ (50 mD to 100 mD)	$N_k = 2:1$ (100 mD to 50 mD)
	
Case Two	
$N_k = 1:3$ (50 mD to 150 mD)	$N_k = 3:1$ (150 mD to 50 mD)
	
Case Three	
$N_k = 1:4$ (50 mD to 200 mD)	$N_k = 4:1$ (200 mD to 50 mD)
	

<table>
<tr><th colspan="2">Case Four</th></tr>
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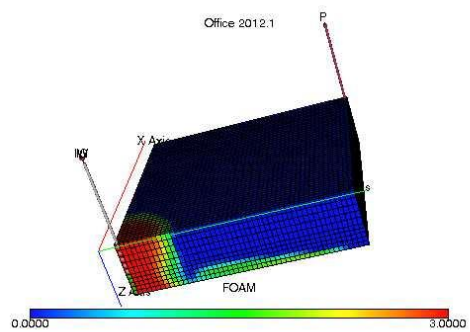
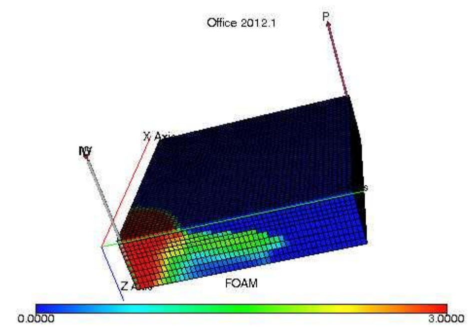
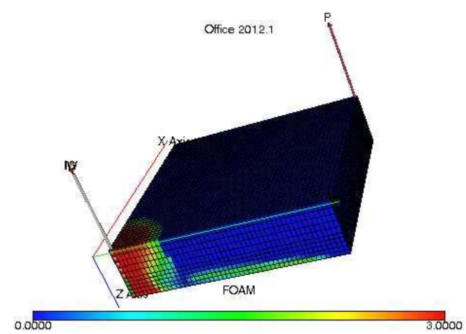
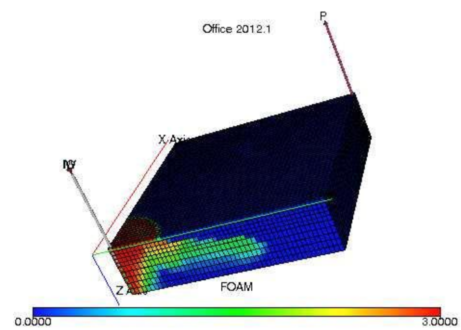
<tr><td>
</td><td>
</td></tr>
<tr><th colspan="2">Case Five</th></tr>
<tr><td>$N_k = 1{:}10$ (50 mD to 500 mD)</td><td>$N_k = 10{:}1$ (500 mD to 50 mD)</td></tr>
<tr><td>
</td><td>
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