FEASIBILITY STUDY OF CO_2 INJECTION FOR ENHANCED SHALE GAS RECOVERY

by

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14570

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

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CERTIFICATION OF APPROVAL

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BACHELOR OF ENGINEERING (HONS)
(PETROLEUM ENGINEERING)

Approved by,

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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 have not been undertaken or done by unspecified sources or persons.

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SITI NURAISYAH BINTI SUHAIMI

ABSTRACT

Hydrocarbon resources from shale gas reservoirs are becoming very important in recent years to fill the gap between demand and supply. The latest technology in well drilling and fracturing have proven to be an effective method for shale gas reservoirs exploitation and has been used in produce hydrocarbon from shale reservoirs. However, the hydrocarbon recovery from shale reservoirs is very low. Hence, this research study will explore more about the feasibility of CO_2 injection to enhance shale gas recovery and find out its screening criteria. The aims of this study are to evaluate the physical mechanism of gas recovery that is adsorption and analyse the effective scenario of CO_2 injection in order to enhanced shale gas recovery. A basic shale gas reservoir model with and without CO_2 flooding is simulated to evaluate its efficiency in enhancing shale gas recovery. The isotherm parameter analysis for CO_2 and CH_4 is also conducted to evaluate the adsorption. The adsorption give impact to the total gas in place. By considering adsorption and injection, the cumulative gas production increase and the average pressure deplete slowly. CO_2 injection has potential in enhanced shale gas recovery as the result shows the increment of gas mass by 1.83%.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious, the Most Merciful. Praise to Him the Almighty that in His will and given strength, the final year project is successfully completed within the allocated eight months period in Universiti Teknologi PETRONAS (UTP). Upon completing the Final Year Project, I owe a great many thanks to a great many people for their help and support, as well as their contribution in time, effort, to advice, supervise, discuss and help during the project period.

First and foremost, deepest thank goes to my helpful supervisor, Mr Mohammad Amin Shoushtari who contributed immensely to my final year project studies right from the beginning until the end. The supervision and support that he gave truly helped the progression and smoothness of this project. The co-operation is much indeed appreciated. It was an honour and privilege to be his student and to complete my final year project under his supervision.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In engineering applications, shale formation is known as one of the most problematic rock types. Shale has certain characteristic features which is very low permeability, the existence of micro-fractures and sensitivity to contacting fluids that make it difficult to evaluate. Production of natural gas from shale formation is characterized as unconventional gas reservoir due to its low permeability (Schepers, Nuttall, Oudinot, & Gonzalez, 2009).

Figure 1 shows the map of major shale plays in United State (US). There are about 20000 wells from 3000 to 5000 ft. depth in the Appalachian basin shale, the Devonian and Lewis shale while the Barnett and Woodford shale are from 2000 to 6000ft. Shale thickness, 300 to 600 ft. are the good shale gas prospect and fractures (Dahaghi, 2010) are the main key in shale plays to get good production.

Unconventional shale gas reservoirs have become a very important part of the resources base throughout the world. In recent years, by having advanced technologies that are horizontal drilling and multistage hydraulic fracturing, shale gas plays was gaining worldwide attention. However, gas production rate from shale reservoirs rapidly decline after a few years of production. Figure 2 shows production rate plot from Barnett shale (Yu, Al-Shalabi, & Sepehrnoori, 2014) and it proved that gas production rate in shale reservoirs rapidly decrease.

According to the estimate made by EIA, the total amount of technically recoverable shale gas in the world is 7,299 trillion cubic feet. Table 1 gives the amount of technically recoverable shale gas of top 10 countries. Proven natural gas reserves of all types refer to amount of proved natural gas, including all conventional and unconventional natural gas. In Russia, amount of estimated technically recoverable shale gas is higher than proven natural gas reserves which mean the potential of shale gas is enormous.

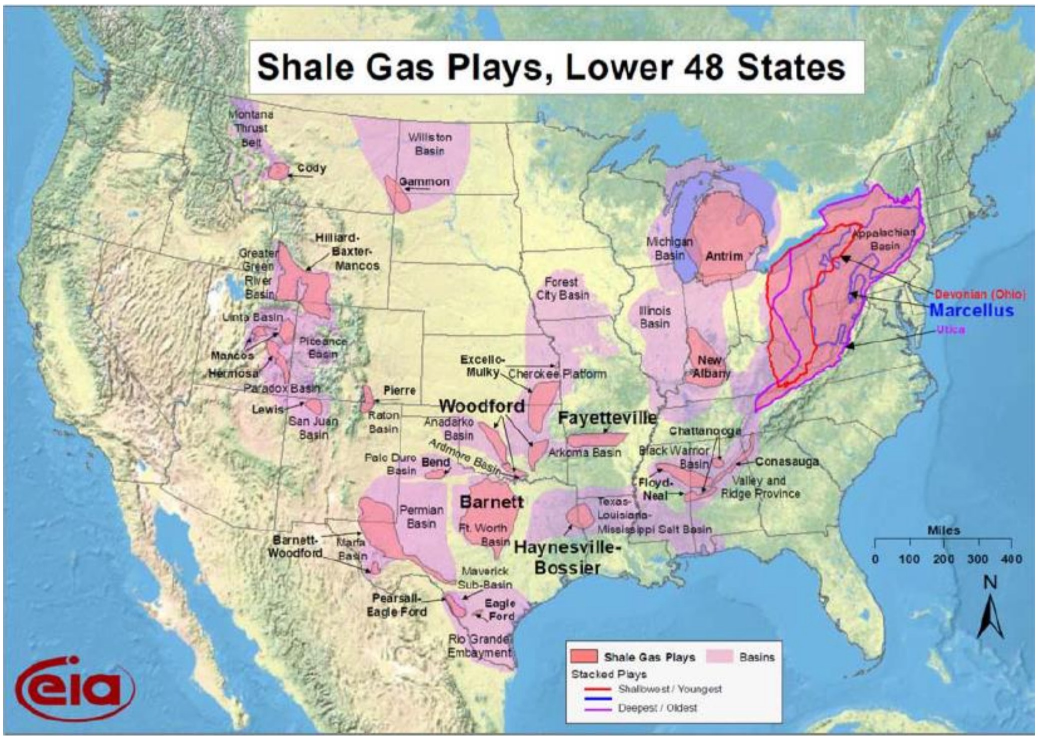


Figure 1: Map of major shale gas plays in the US (EIA, 2011)

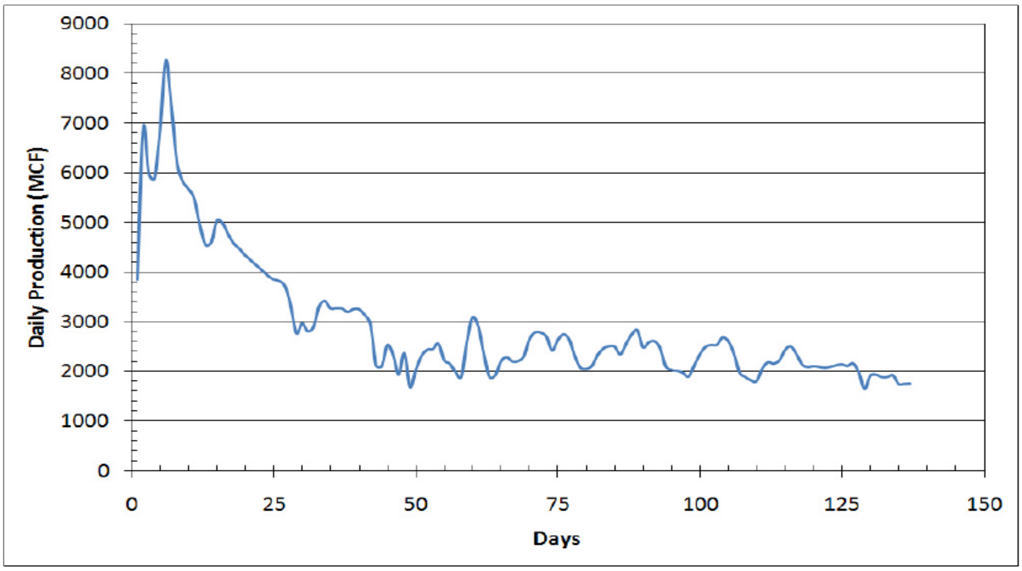


Figure 2: Daily production rate of the Barnett shale study area (Vermylen, 2011)

Table 1: Shale gas (EIA, 2013)

	Country	Estimated recoverable (trillion cubic feet)	Proven reserves (trillion cubic feet)
1	China	1115	124
2	Argentina	802	12
3	Algeria	707	159
4	United States	665	318
5	Canada	573	68
6	Mexico	545	17
7	South Africa	485	-
8	Australia	437	43
9	Russia	285	1688
10	Brazil	245	14

1.2 Problem Statement

Currently, advanced technologies which is horizontal drilling and multistage hydraulic fracturing made the shale gas plays gained worldwide attention. After a few years of production, gas production rate from shale reservoirs rapidly decline. For conventional reservoirs, CO_2 injection is widely applied to enhance oil recovery. However, application of CO_2 injection in shale gas reservoir is a new and challenging concept as shale formation is tight and unconventional reservoir. Hence, a feasibility study of applying CO_2 injection in shale gas reservoirs is required in order to evaluate the potential of CO_2 injection in shale gas and analyse the physical mechanism of gas recovery in shale formation.

1.3 Objectives of Study

- To evaluate the physical mechanism of gas recovery in shale reservoir.
- To analyse the effective scenario of CO_2 injection for enhanced shale gas recovery.

1.4 Scope of Study

The scope of study is mainly to study on the books, journals and related articles about the CO_2 injection in shale gas reservoirs in enhancing gas recovery. The scope of study is divided into three stages.

The first stage is about the physical mechanism of gas recovery. In this stage, it involve the evaluation of adsorption of CO_2 and CH_4.

The second stage is about the scenario of CO_2 injection for enhanced shale gas recovery which is CO_2 flooding and CO_2 huff and puff. These scenario are compared and evaluated with the support of simulation result from previous research for various shale gas field.

The third stage is work on the simulation regarding the recovery of shale gas using GEM simulator. The data for simulation is taken from previous research paper. The simulation with and without CO_2 are conducted to compare with previous research and prove the feasibility of using CO_2 flooding.

CHAPTER 2

LITERATURE REVIEW

2.1 Shale Gas Reservoir vs. Conventional Gas Reservoir

Shale gas is a natural gas that is trapped within shale formations. Shale is a source rock, a reservoir and a trap of natural gas. Production of gas from shale is often referred as unconventional. Shales are fine-grained sedimentary rocks that can be rich resources of petroleum and natural gas. Sedimentary rocks are rocks formed by the accumulation of sediments at the Earth's surface and within bodies of water. Common sedimentary rocks include sandstone, limestone, and shale. Conventional oil and gas refers to hydrocarbons which have previously sought in sandstone or limestone, instead of shale or coal. Conventional reservoir is easier to produce than unconventional reservoir.

Table 2: Comparison shale gas and conventional

Shale Gas Reservoir	Comparison	Conventional Gas Reservoir
Very low permeability : 0.001 to 0.0000001mD	Permeability	High permeability : 1mD to 1D
Low gas recovery	Recovery	High gas recovery
Shale	Types of formation	Sandstones

Figure 3: Types of conventional and unconventional reservoir

2.2 Shale Formation Characteristics

Shale is the most abundant sedimentary rock and is characterized by thin grains and thin lamina breaking with an irregular curving fracture which is parallel to the bedding plane (Tom Alexander, Baihl, & Boyer, 2011). Due to its unique features included low permeability, low compressive strength, the existence of micro-fractures, and high sensitive to water make shale the most problematic rock type in engineering application.

Shale has a high total organic carbon (TOC) (Yu, Sepehrnoori, & Patzek, 2014) because it's deposited under conditions of little or no oxygen in the water. TOC is a fundamental attribute of shale gas and is a measure of organic richness. The TOC content, thickness of organic shale and organic maturity (Yu, Al-Shalabi, et al., 2014) are key attributes that aid in determining the economic viability of a shale gas play. At higher value of TOC, more gas is generated and vice versa (Table 3). Shale are the source rock for oil and natural gas and it's migrate out of the shale to the pore spaces of sandstone formation because of their low density. Shale also acts as seal rock that trap oil and gas in sandstone formation.

Table 3: Relationship between TOC and resources potential (Tom Alexander et al., 2011)

Total organic carbon (TOC), weight %	Resources potential
<0.5	Very poor
0.5 to 1	Poor
1 to 2	Fair
2 to 4	Good
4 to 10	Very good
>10	Unknown

Shale can be grouped in two categories based on its colours; the first category is gray black shale that contain 1% or more free carbonaceous material. The second category is red-brown-yellow-green colour shales which is contain the presence or absence of iron oxide. Shale is composed mainly of clay-size mineral grains, which are usually clay minerals such as illite, kaolite, quartz, chert, feldspar and smectite.

The permeability of shale can range from 0.001 to 0.0000001mD (Tom Alexander et al., 2011). In shale formations, nano-pores to micro-pores are representative of shale permeability which is depend on the rock type; compacted or cemented, depth of burial, pressure and the history of diagenesis (Asef & Farrokhrouz, 2013). Shale reservoir possess very low permeability.

Shale porosity varies from less than 1% to more than 50% and it depends on the depth of burial and the degree of compaction or cementation (Asef & Farrokhrouz, 2013). Shale was categories as dual porosity systems (Yan, Wang, & Killough, 2013). It contains both primary and secondary porosity systems. The primary porosity from micro-pores and meso-pores contains the majority of gas in place and gas storage dominated by adsorption. Whereas secondary porosity (macro pore and natural fractures) provides the conduit for mass transfer to the wellbore and it’s dominated by diffusion and Darcy flow.

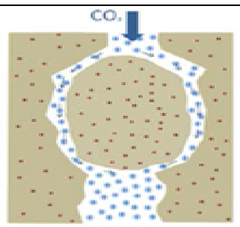
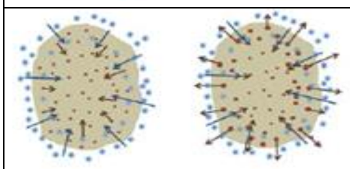
2.3 Horizontal Well with Multi-Stage Hydraulic Fracturing

Hydraulic fracturing application has been widely used in the industry for improving the productivity of unconventional reservoirs. Hydraulic fracturing are used to reduce formation damage and increase the conductivity of flow path of fluid to wellbore. Propped hydraulic fracturing is aimed at raising the well productivity by increasing the effective wellbore radius for wells completed in low permeability or clastic formations.

Horizontal well is well with inclination greater than 85^{o} drilled to enhance the contact area with formation by placing a long wellbore section. Horizontal well with multi-stage fracturing is very important in producing gas from ultralow permeability shale reservoirs. It is because the well productivity in shale is dominated by the conductivity of fracture system.

2.4 Mechanism of CO_2 injection in shale

Figure 4 shows the conceptual mechanism of CO_2 injection in shale reservoir as follows: (1) CO_2 was injected rapidly through the fractures, (2) CO_2 was started to permeate rock either carries hydrocarbon into rock which is bad or pushes hydrocarbon out of the rock which is good, (3) Hydrocarbon migrates to bulk CO_2 in fractures based on swelling and lower viscosity, (4) CO_2 pressures equalize inside of rock and hydrocarbon is swept to production well (Hawthorne et al., 2013).

	Step 1 Initial injection: CO_2 flows rapidly through fractures.
	Step 2 CO_2 starts to permeate rock based on pressure gradient.

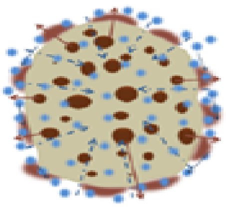
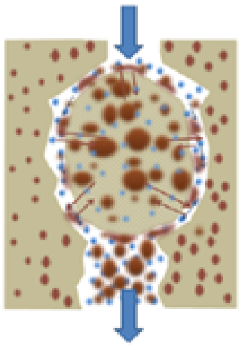
	Step 3 As CO_2 permeates into the rock, hydrocarbon migrates to bulk CO_2 in fractures based on swelling and lower viscosity.
	Step 4 CO_2 pressures equalize inside the rock. ➢ Hydrocarbon production is now based only on concentration gradient driven diffusion. ➢ Hydrocarbon in bulk CO_2 is swept through fractures to production well.

Figure 4: The process of CO_2 in shale recovery (Hawthorne et al., 2013)

2.4.1 Adsorption mechanism

Sing et al. (1985) stated that adsorption is the attachment of one or more components in a layer. There are six type of adsorption as shown in figure 5. Based on research by Vermylen (2011), the Langmuir isotherm (Type I) demonstrated adsorption model for CH_4 and Brunauer Emmet Teller (BET) isotherm (Type II) demonstrated adsorption model for CO_2. The equation for Langmuir isotherm is:

$$V\,(P) = \frac{V_L P}{P + P_L}$$

Where V(P) is the gas volume of adsorption at pressure, P; P is pore pressure; V_L is Langmuir volume and P_L is Langmuir pressure.

BET isotherm model is a generalization of Langmuir model to multiple adsorbed layers (Yu, Sepehrnoori, et al., 2014). The expression is as below:

$$V(P) = \frac{V_m C \frac{P}{P_o}}{1 - \frac{P}{P_o}} \left(\frac{1 - (N+1)\left(\frac{P}{P_o}\right)^N + N\left(\frac{P}{P_o}\right)^{N+1}}{1 + (C-1)\frac{P}{P_o} - C(\frac{P}{P_o})^{N+1}} \right)$$

Where V(P) is gas volume of adsorption at pressure, P; P is pore pressure; Vm is maximum adsorption gas volume; Po is saturation pressure; C is constant related to the net heat of adsorption; N is maximum number of adsorption layers.

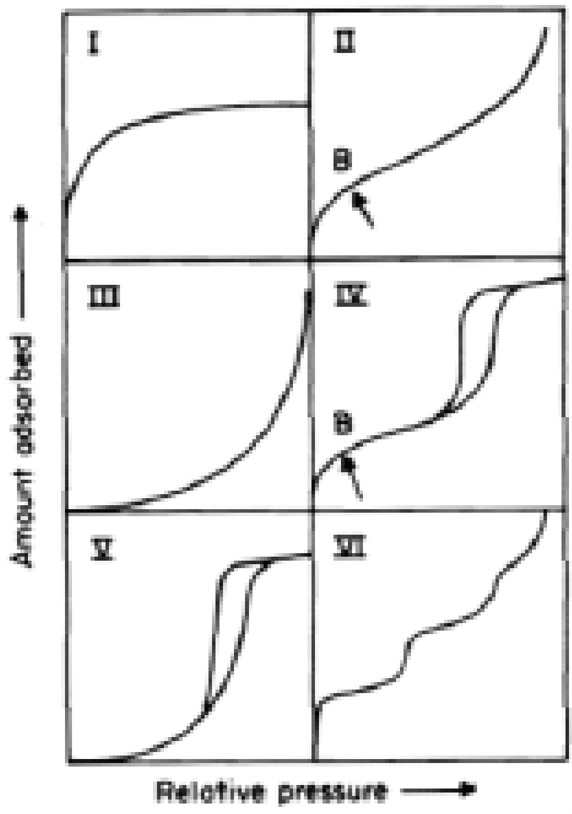


Figure 5: Different types of adsorption (Sing et al., 1985)

2.5 CO_2 Injection for Enhanced Gas Recovery

Enhanced gas recovery by injection CO_2 is not broadly investigated as the gas field has high recovery through natural depletion and have potential in unwanted mixing of gas and CO_2. Enhanced gas recovery for conventional reservoir is occurs by CO_2 displacement and repressurisation of the reservoir (Al-Hasami, Ren, & Tohidi, 2005). Al-Hasami et al. (2005) summarised the benefits of CO_2 injection that are the nearly gas-like viscosity of the supercritical CO_2 allow a high injection of CO_2 into the formation, low mobility ratio than CH_4, high solubility in water and lastly, density of CO_2 greater than CH_4. Based on the research by Al-Hasami et al., CO_2 injection into conventional gas reservoir is viable as it give 8-11% gas recovery increment.

2.5.1 CO_2 and CH_4 properties

Typically, CO_2 behave as a super critical fluid at deep reservoir conditions which has viscosity and density of a liquid. Density and viscosity of CO_2 and CH_4 changes with depth (Figure 6). Kalra and Wu (2014) stated that the suitable formation depth for CO_2 injection and enhanced gas recovery is 4000 ft and above as density and viscosity plot for CO2 and CH4 shows significant contrast. CO_2 is highly denser than CH_4 throughout the reservoir pressure range and highly viscous property of CO_2 than CH_4 with respect to formation depth (Kalra & Wu, 2014).

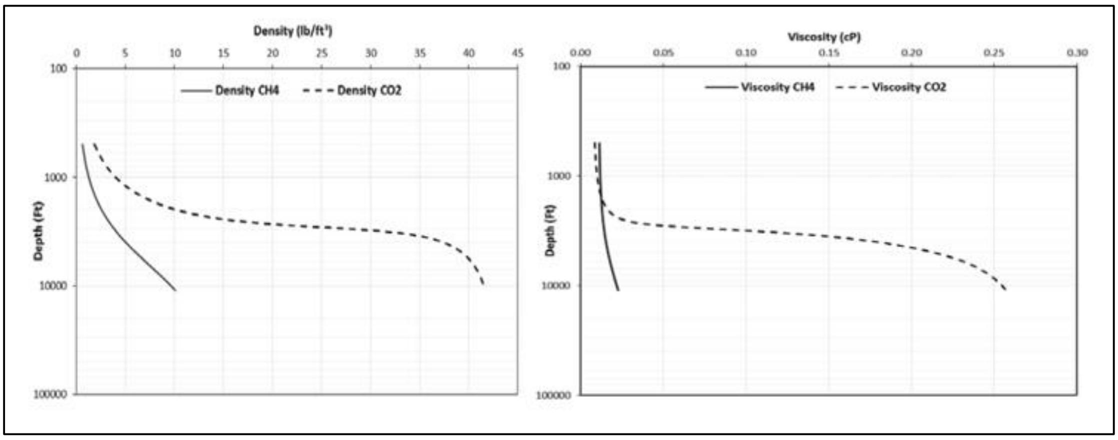


Figure 6: Density and viscosity comparison of CO_2 and CH_4 (Kalra & Wu, 2014)

2.5.2 Types of CO_2 Injection

Most of the research paper about enhancing shale gas recovery simulated two types of CO_2 injection scenario which is CO_2 flooding scenario and CO_2 huff-n-puff scenario. CO_2 flooding scenario is where one horizontal production well is converted to injection well. CO_2 is injected into reservoir and the other production wells are produced all the time.

Whereas, CO_2 huff-n-puff scenario (Yu, Al-Shalabi, et al., 2014) consists of three main stages: (1) CO_2 injection, (2) CO_2 soaking, (3) Production (Figure 9). In the first stage, production wells are converted to injection wells and CO_2 is injected. Then after certain period of CO_2 injection, all injection wells are shut in for another period as a soaking time. Finally, all wells are produced back until end of production period. Yu, Al-Shalabi, et al. (2014) conclude that CO_2 flooding is the best option for the process of enhance shale gas recovery because CO_2 injection by huff-n-puff scenario reproduced CO_2 quickly to the surface. Figure 7 shows the result cumulative gas produce with and without CO_2 flooding scenario while Figure 8 for with and without CO_2 huff-n-puff scenario.

It is concluded that enhancement of gas during flooding scenario could be pressure maintenance by CO_2 injection while during huff-n-puff scenario, gas recovery decreased due to large amount of CO_2 backflow. Schepers et al. (2009) stated that huff-n-puff scenario is not applicable to shale production due to reproduction of CO_2 quickly although increasing the soaking time and decreasing the thickness of reservoir. Flooding scenario seems to be potential success as it is showing a significant gain in recovery and by decreasing the thickness of reservoir, the recovery percentage increase.

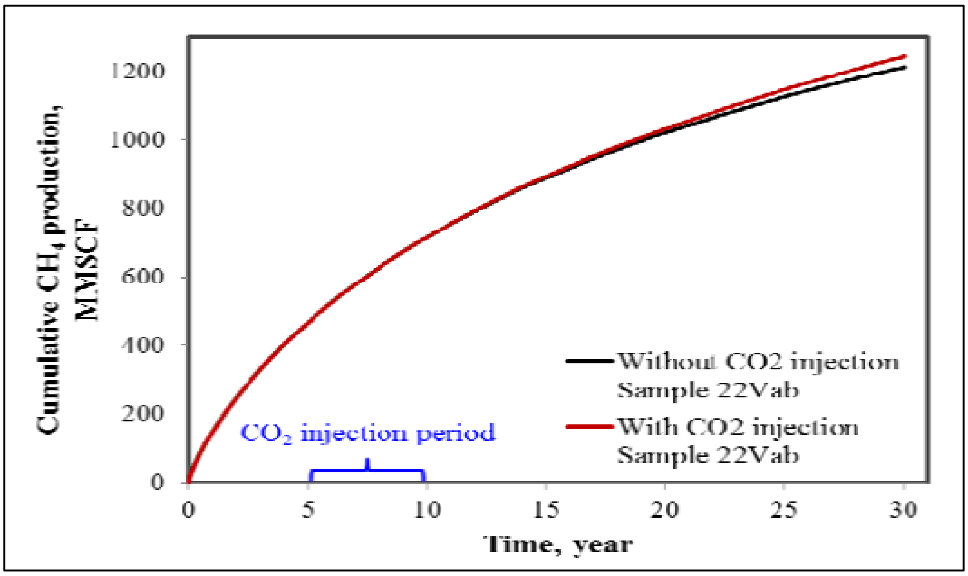


Figure 7: Comparison of gas production with and without CO_2 flooding (Yu, Al-Shalabi, et al., 2014)

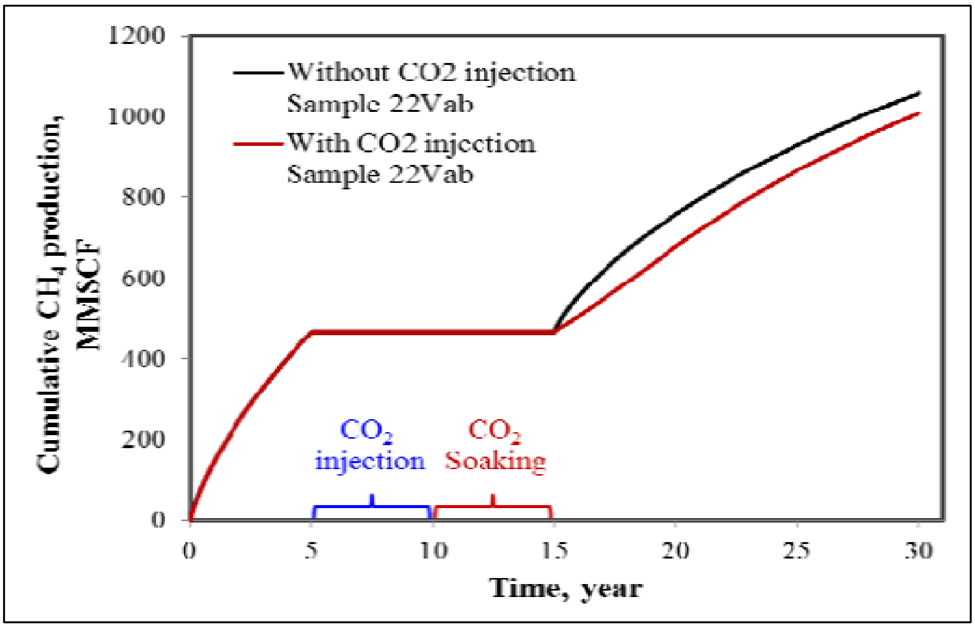


Figure 8: Comparison of gas production with and without CO_2 huff-n-puff (Yu, Al-Shalabi, et al., 2014)

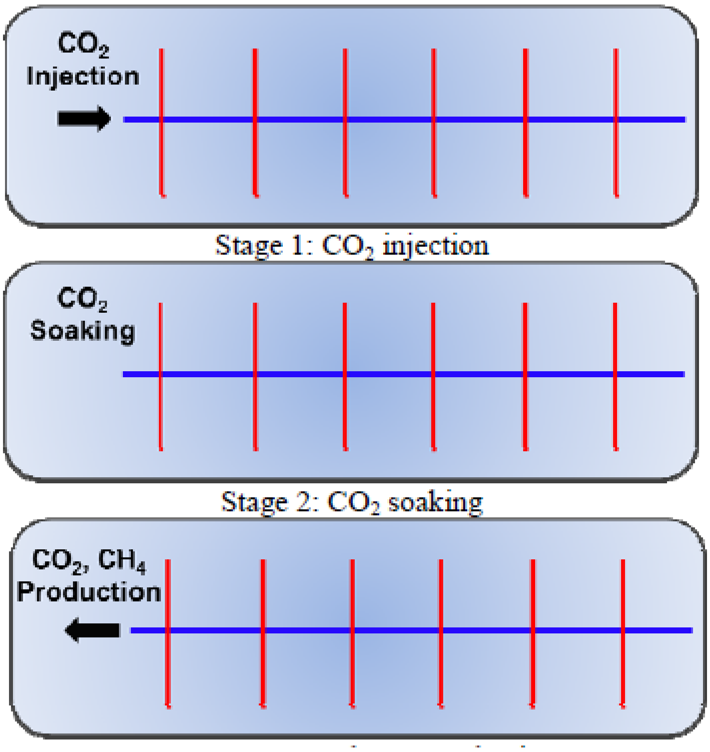


Figure 9: The stages of CO_2 huff-n-puff (Yu, Al-Shalabi, et al., 2014)

CHAPTER 3

RESEARCH METHODOLOGY

A few methodologies are conducted to complete this project in achieving its objectives. The first method is literature review. A thorough studies on the shale reservoir characteristics, mobilization mechanism of CO_2, hydraulic fracturing and injection method of CO_2 by referring to numbers of SPE papers, articles and journals. Then, the case studies which related to the project are analysed and evaluated to examine critically the feasibility of CO_2 injection for enhanced shale gas recovery. Next, the mechanism of gas recovery, effective method of CO_2 injection and screening criteria of using CO_2 for enhanced shale gas recovery are evaluated. Finally, the findings and results are discuss and give conclusion from this project work as well as recommendations for future research.

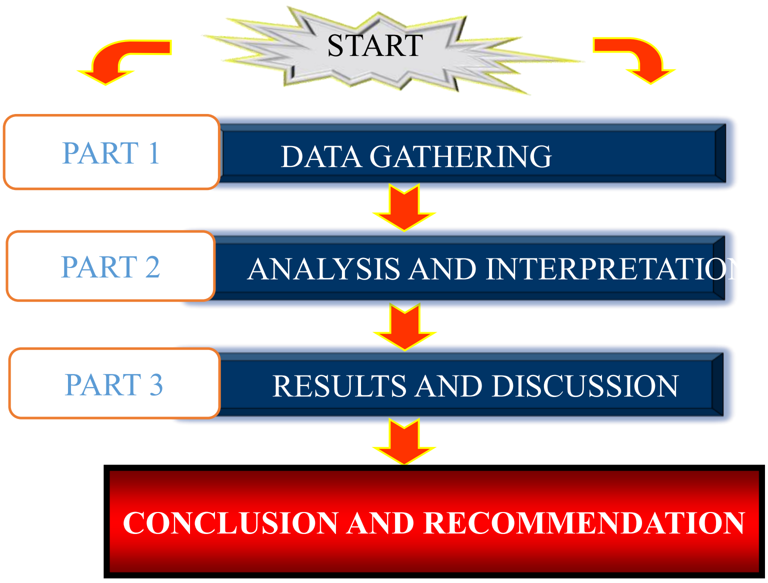


Figure 10: Research methodology diagram

3.1 Tools

Several tools and software has been used throughout this project. All tools and software used are listed in required Table.

Table 4: Tools and software required

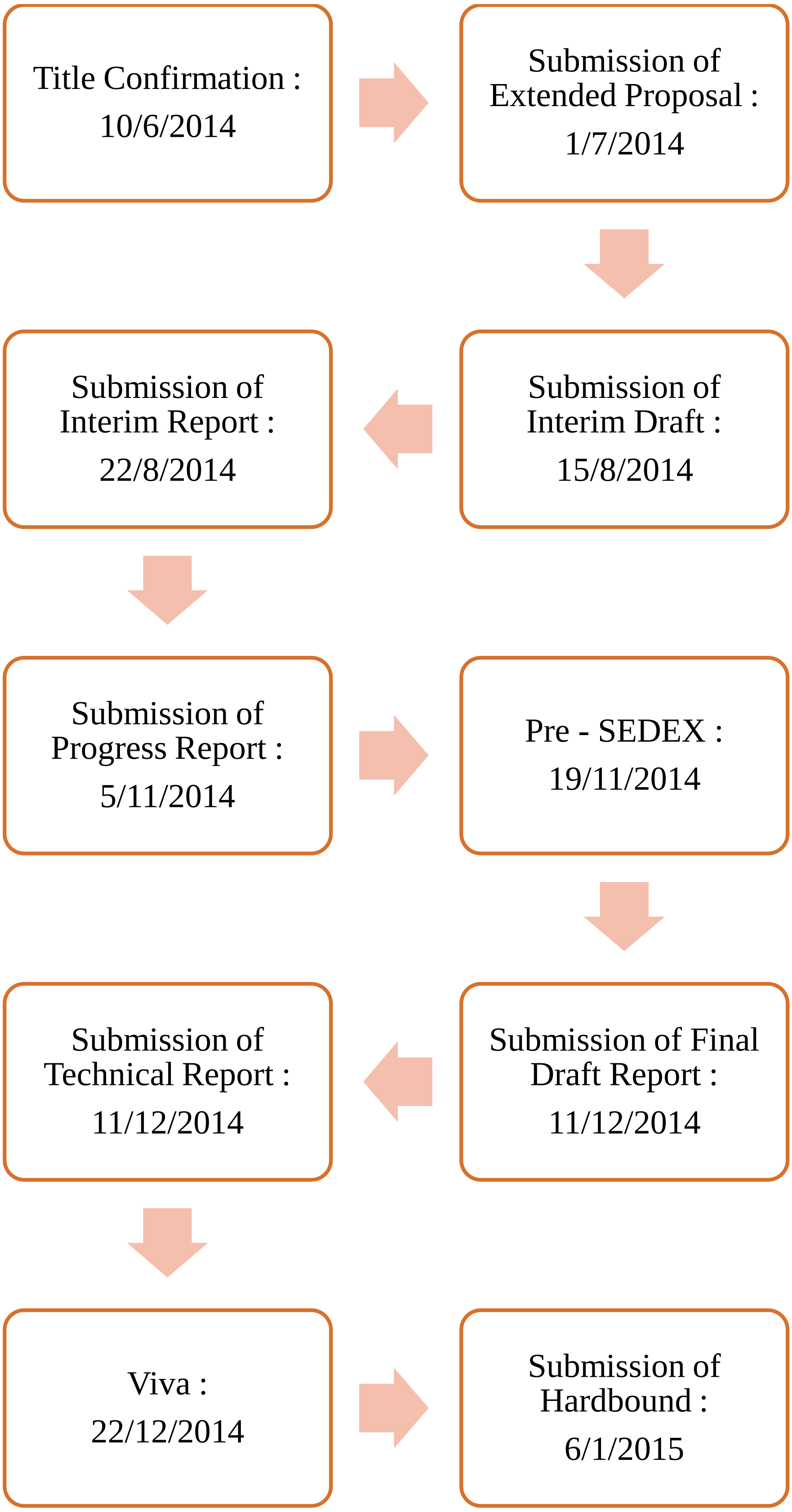
Tools / Software	Purpose
Microsoft Office Word	Documentation of project report
Microsoft Office Excel	Project planning, adsorption calculation
GEM simulator	Modelling shale gas reservoir
RESULTS	Visualize and report GEM input and output data
EndNote	Manage bibliographies, citation and references

3.2 Gantts Chart

			Final Year Project I													
		Month	**MAY**		**JUNE**				**JULY**				**AUGUST**			
Progress		**Dateline**	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Selection of project	Choosing title from coordinator	10/6/2014														
Preliminary Research Work	Collection of related research paper															
	Background of study															
	Problem statement															
	Objectives of study															
	Scope of study															
Research Literature Review	shale formation study															
	mobilization mechanism of CO_2 study															
	hydraulic fracture orientation study															
	injection modes of CO_2 study															
Research Methodology	Gantts chart															
	Key milestones															
Submission of Extended Proposal	meeting with supervisor	16/6/2014 19/6//2014 24/6/2014 1/7/2014														
Proposal Defence		14/7/2014														
Research Literature Review	huff n puff method study															
	CO_2 flooding study															
Research Methodology	methodology of research															
Interim Draft	Submission	15/8/2014														
Interim Report	Submission	22/8/2014														

			Final Year Project II															
		Month	**SEPTEMBER**				**OCTOBER**				**NOVEMBER**				**DECEMBER**			
Progress		**Dateline**	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24	W25	W26	W27	W28	W29	W30
FYP II Briefing																		
Project Work	Work on simulation																	
	Adsorption study																	
	Gas transport study																	
Progress Report	Submission	5-Nov-14																
Pre - Sedex	Preparing Poster																	
	Presentation	19-Nov-14																
Final Report Preparation	Literature Review																	
	Methodology																	
	Results and Discussion																	
	Conclusion and Recommendation																	
Final Draft Submission		11-Dec-14																
Technical Report Submission	edit final draft																	
	submission	11-Dec-14																
Viva	prepare slide presentation																	
	presentation	22-Dec-14																
Hardbound Submission	prepare hardbound																	
	Submission	6-Jan-15																

3.3 Key milestones



3.4 Simulation of shale gas reservoir

The data used in basic reservoir model is taken from a study by Yu, Al-Shalabi, et al. (2014). The data used for modelling basic reservoir model is shown in Table 5. In this study, a shale reservoir with the area of about 326 acres is producing from two horizontal wells which is each well is stimulated with ten (10) fracturing stage and 1000ft well spacing (Figure 11). The assumptions for this reservoir model are homogeneous and evenly spaced fractures. The Langmuir isotherm parameter for methane and Braneur Emmet Teller (BET) isotherm parameter for CO_2 are shown in table 6. The shale gas reservoir model with and without CO_2 injection are simulated by using GEM simulator. Post-processing of GEM simulator (RESULTS) is used to view the output of these simulations.

Table 5: Parameter basic reservoir (Yu, Al-Shalabi, et al., 2014)

Parameter	Value(s)	Unit
Dimensions	5000(L) x 3000(W) x 300(H)	ft
Depth	6481	ft
Pore pressure gradient	0.54	Psi/ft
Initial reservoir pressure	3500	Psi
Closure pressure	4602	Psi
Closure pressure gradient	0.71	Psi/ft
Bottom hole pressure (BHP)	300	Psi
Production time	30	Year
Reservoir temperature	150	^oF
Initial gas saturation	0.7	Value
Specific gas gravity	0.58	Value
Total compressibility	3×10^{-6}	Psi^{-1}
Matrix permeability	500	nD
Matrix porosity	0.06	Value
Fracture conductivity	10	mD-ft
Fracture half-length	425	ft
Stage spacing	450	ft
Fracture height	300	ft
Horizontal well length	4100	ft
Total number of fractures	20	Value

Table 6: BET and Langmuir isotherm parameters (Vermylen, 2011)

Sample	CO_2				CH_4	
	P_o (psia)	V_m (scf/ton)	C	N	P_L (psia)	V_L (scf/ton)
31Vcde	927	55.5	9	10.2	335	45.4
22 Vab	927	35.3	10.1	9.3	702	55

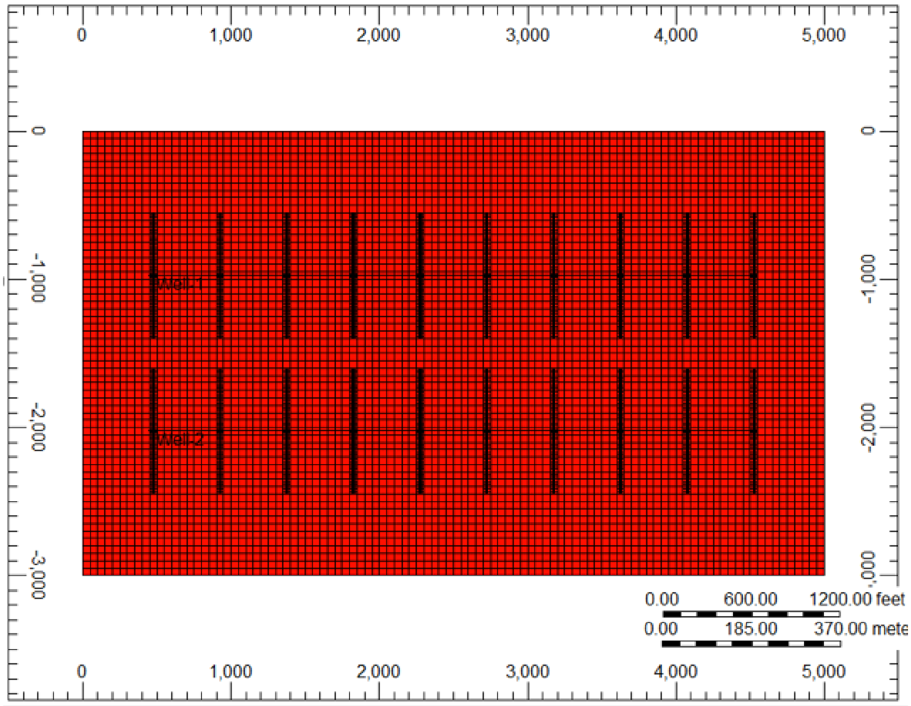


Figure 11: Reservoir model with two horizontal wells

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Adsorption

The amount of adsorption give impact to the total gas in place. Based on the experiment conducted by Vermylen (2011), adsorption tests on Barnett samples match with Langmuir isotherm for methane and BET isotherm for carbon dioxide. Table 7 shows the data for Langmuir and BET isotherm parameters for Barnett shale and the plot of adsorption for Barnett shale is shown in Figure 12.

Table 7 : Isotherm parameter on Barnett shale sample

Isotherm parameters	CH4 (A) (22Vab)	CH4 (B) (31Vcde)	CO2 (A) (22Vab)	CO2 (B) (31Vcde)
Lp (psia)	702	335		
Lv (scf/ton)	55	45.4		
Po			927	927
Vm			35.3	55.5
C			10.1	9
N			9.3	10.2
Isotherm Temp (F)	150	150	150	150

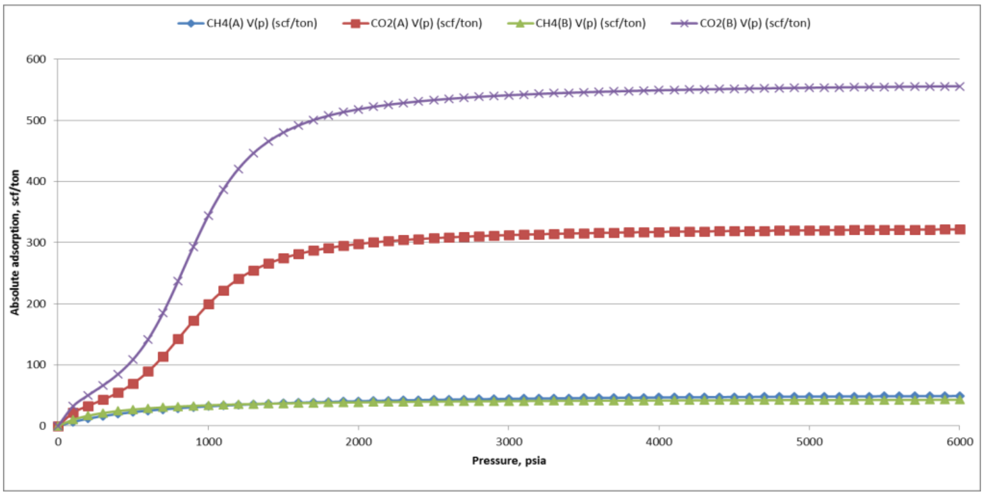


Figure 12 : Pressure vs. adsorption plot for Barnett samples

Whereas, the findings of adsorption test on Devonian shale sample are Langmuir isotherm for methane and carbon dioxide (Schepers et al., 2009). The data of isotherm parameter for Devonian shale is shown in Table 8. The plot of this adsorption capacity is shown in Figure 13.

Table 8 : Isotherm parameter on Devonian shale

Isotherm parameters	CH4	CO2
Lp (psia)	443.2	243.7
Lv (scf/ton)	34.6	67.6
Isotherm Temp (F)	86	86

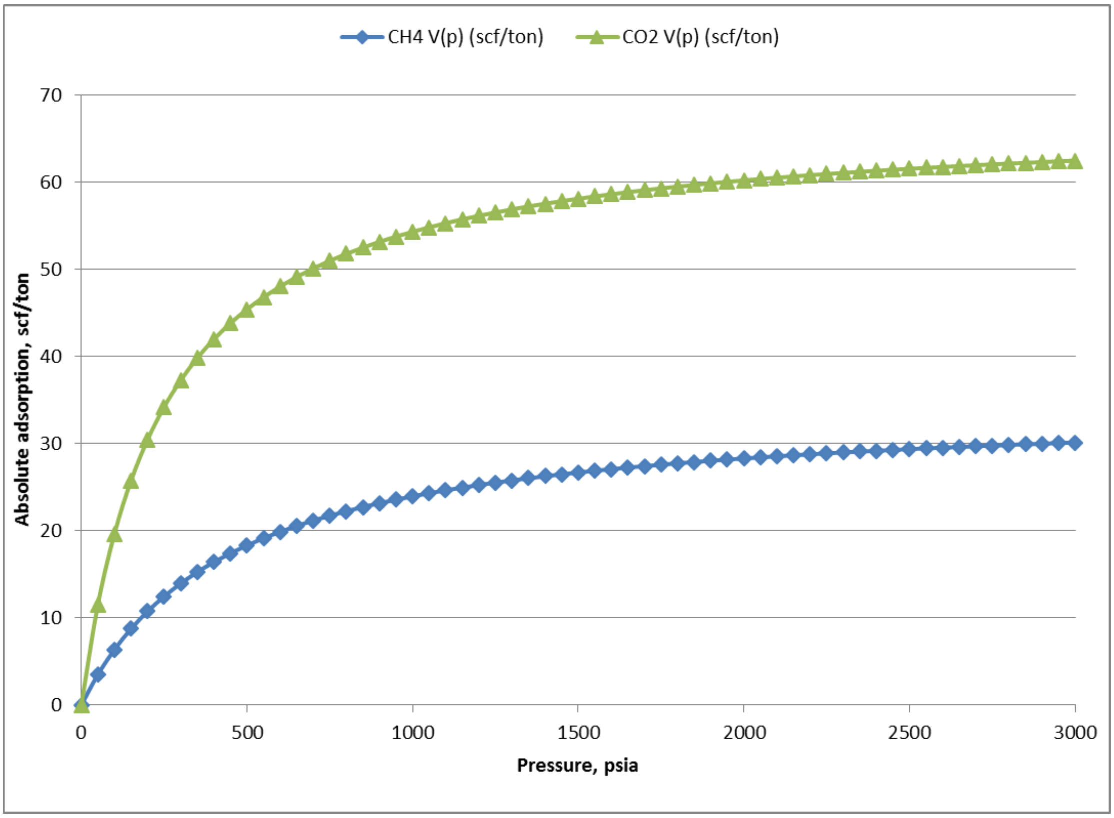


Figure 13 : Pressure vs. adsorption plot for Devonian samples

The sensitivity analysis on methane sorption volume and pressure are performed to evaluate the effect of sorption isotherm on cumulative gas production and selectivity ratio is calculated (Dahaghi, 2013). Dahaghi (2013) summarizes the selectivity ratio for isotherm parameter that used in this study. The equation used to calculate selectivity ratio is expressed as:

$$\propto = \frac{(VL - CO2 \ * \ PL - CH4)}{(VL - CH4 \ * \ PL - CO2)}$$

Table 9: Selectivity ratio for isotherm parameter of Barnett shale sample

	Methane		Carbon dioxide		Selectivity ratio, $\propto$
	V_L(mscf/ton)	P_L(psi)	V_m(Mscf/ton)	P_m(psi)	
Case 22Vab	0.055	702	0.0353	927	0.486
Case 31Vcde	0.0454	335	0.0555	927	0.442

4.1.1 Effect of Adsorption on Shale Gas Recovery

Type of isotherm that match with the experiment data is significant in evaluate the gas recovery. From figure 12 and figure 13, result of adsorption test on Devonian shale sample and Barnett shale sample are different for CO_2. This is because the range of pressure for Barnett sample is higher than Devonian sample. As the plot of adsorption for Barnett is change to low pressure, it is shown CO_2 also match with Langmuir isotherm. From this adsorption plot, it showed that six (6) to ten (10) times of CO_2 most preferable to adsorb on the layer than CH_4. As the pressure increase, the adsorption capacity also increasing. In order to desorb the CH_4 from shale matrix, a very low pore pressure is needed or injection of CO_2.

The selectivity ratio for case 22Vab is higher than case 31Vcde which is the sorption volume of CH_4 larger than CO_2 will increase the cumulative gas produce. Figure 14 shows the cumulative gas produce in three cases which is none adsorption, with adsorption case 22Vab and with adsorption case 31Vcde. Increasing CH_4 sorption volume improve the cumulative gas produces. Based on this analysis, adsorption need to consider in evaluate shale gas recovery as it showed increment 4% to 12%. Adsorption case 22Vab is used in simulation of CO_2 injection scenario to analyse and evaluate the effect of CO_2 injection.

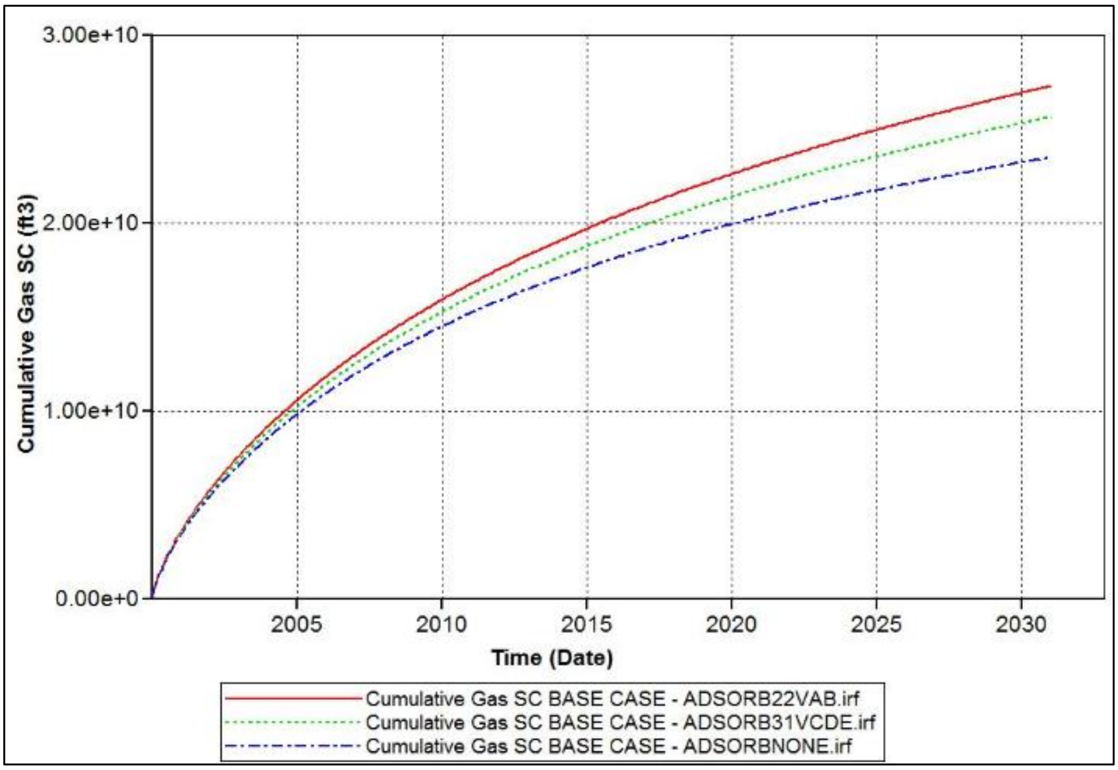


Figure 14 : Comparison cumulative gas plot for all three cases

4.2 CO_2 Injection Methods

Different scenarios of CO_2 injections methods are conducted to evaluate its efficiency in enhancing shale gas recovery. The base case without CO_2 injection is run with two horizontal wells producing at bottom hole pressure of 300 psi for about 30 years. The base case result in term of cumulative gas mass produce is compared with and without CO_2 huff-n-puff scenario and CO_2 flooding scenario.

4.2.1 CO_2 Huff n Puff

The first case scenario of injection, CO_2 huff-n-puff, is run with both wells produce and then after five (5) years, the wells are changed to injection wells for another five (5) years. Next, the CO_2 soaking period for another 5 years and continue produce until the end of production. Figure 15 shows the comparison of cumulative gas mass produce for with and without CO_2 huff-n-puff for Barnett Shale. Huff-n-puff scenario is the bad option for enhanced shale gas recovery as it showed decrement about 1.7% in total gas mass produce. The sensitivity analysis on injection period and soaking time also give no significant effect in enhancing shale gas recovery (Schepers et al., 2009).

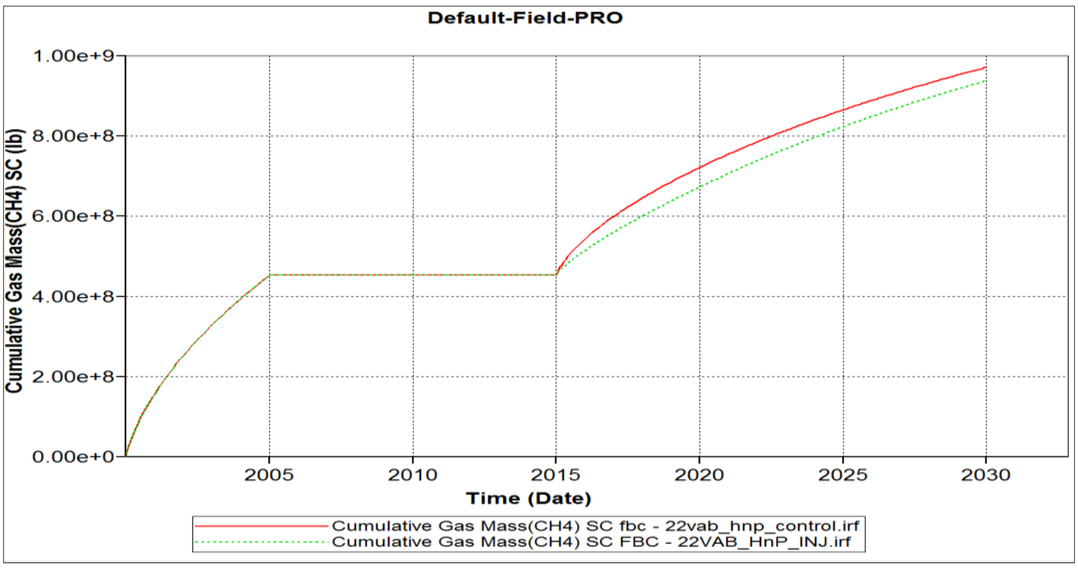


Figure 15: Comparison cumulative gas mass produce for CO_2 huff-n-puff

4.2.2 CO_2 Flooding

The second case scenario of injection, CO_2 flooding, is run with both wells are producing for 5 years and one of the wells is converted to injection well for next 5 years and stop injection. Only one well is producing for the remaining period of production. Figure 16 shows the comparison of cumulative gas mass produce for with and without CO_2 flooding. CO_2 flooding increase the gas recovery by 1.83%. Comparison of average pressure for adsorption and no adsorption during CO_2 flooding and without CO_2 flooding is shown in figure 17. Based on figure 17, the injection of CO_2 flooding maintain the average reservoir pressure. It can be concluded that the process of repressurizing enhanced shale gas recovery.

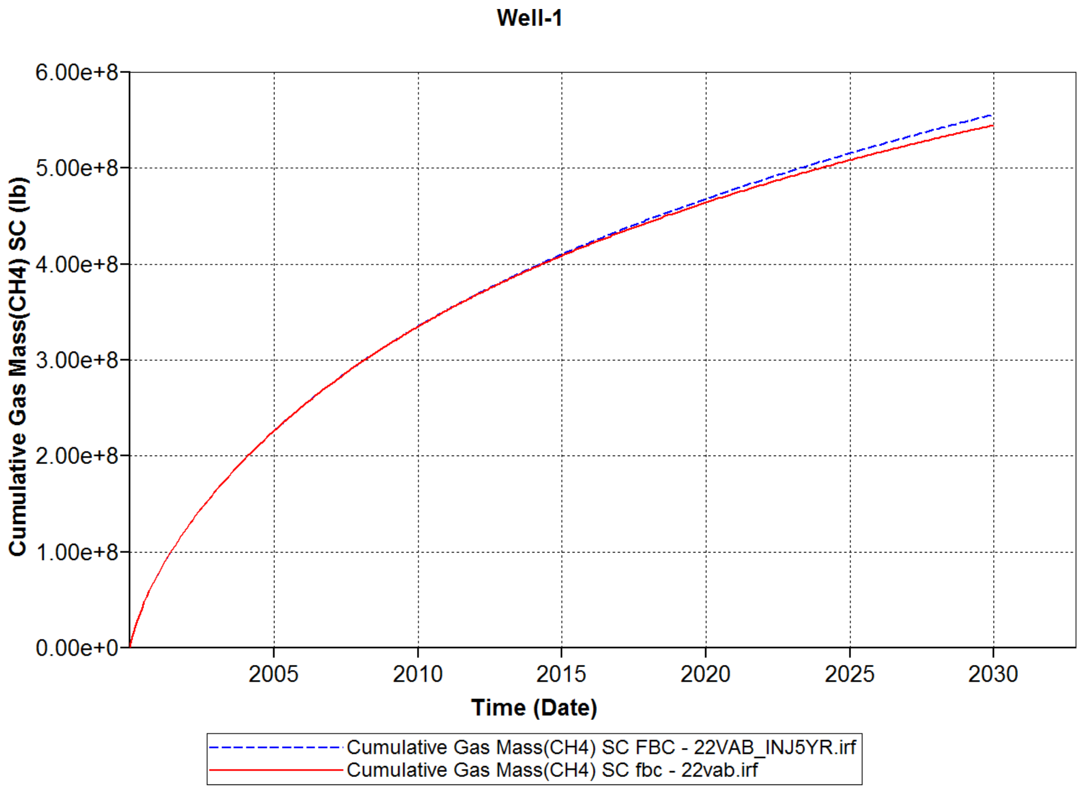


Figure 16: Comparison of cumulative gas mass produce for CO_2 flooding

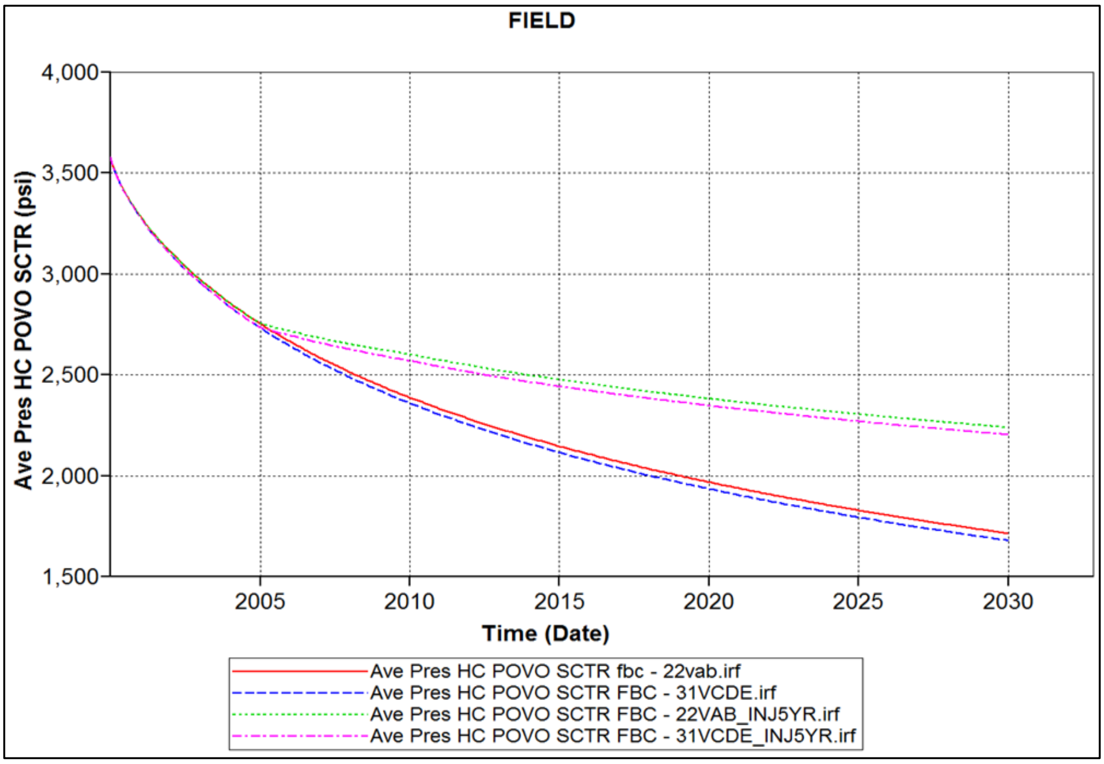


Figure 17 : Comparison of average pressure vs. time for adsorb and non-absorb after CO_2 flooding and without CO_2 flooding

Throughout figure 18 to figure 23, its show the distribution of CO_2 moles, CH_4 moles, and pressure in shale matrix before and after the production and CO_2 flooding.

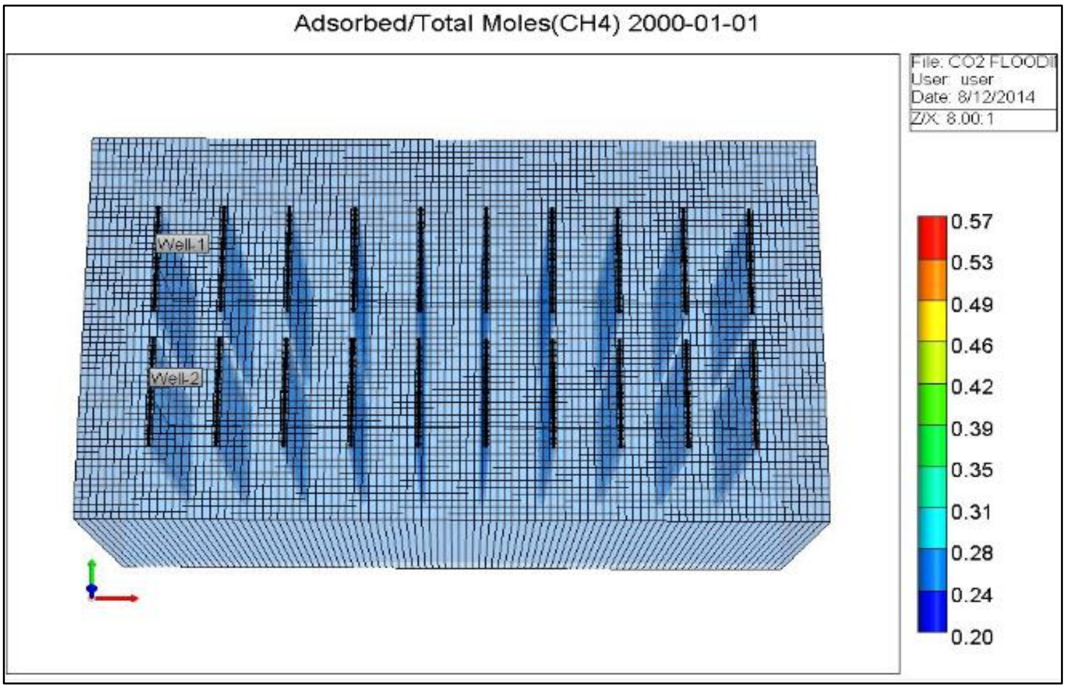


Figure 18 : Shale matrix CO_2 moles distribution before production and CO_2 flooding

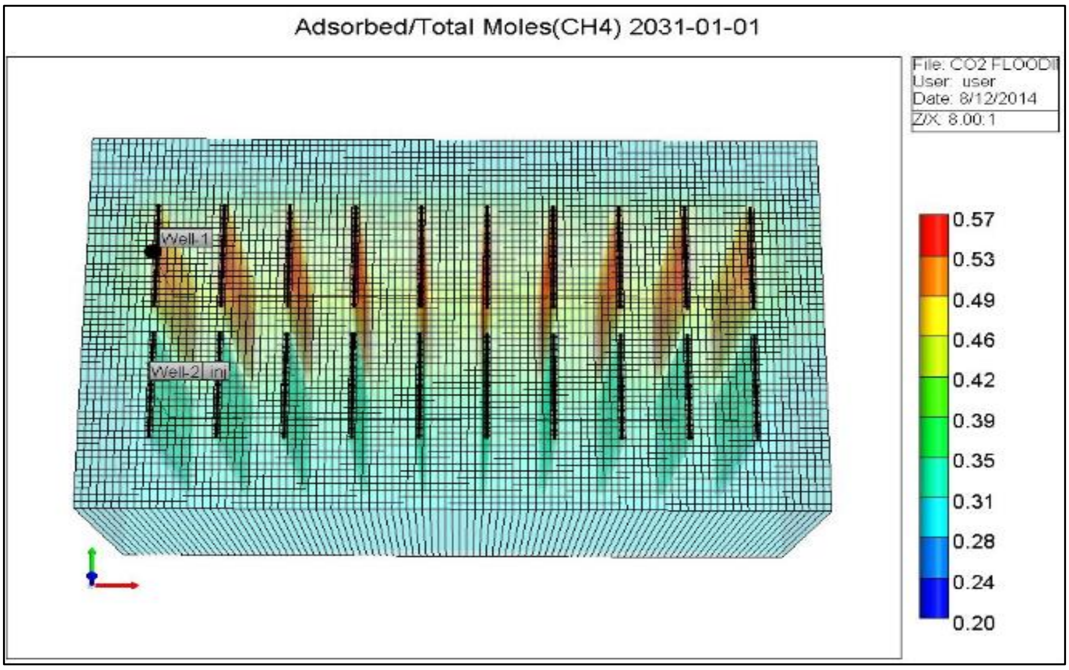


Figure 19 : Shale matrix CH_4 moles distribution after 30 years of production and 5 years of CO_2 flooding

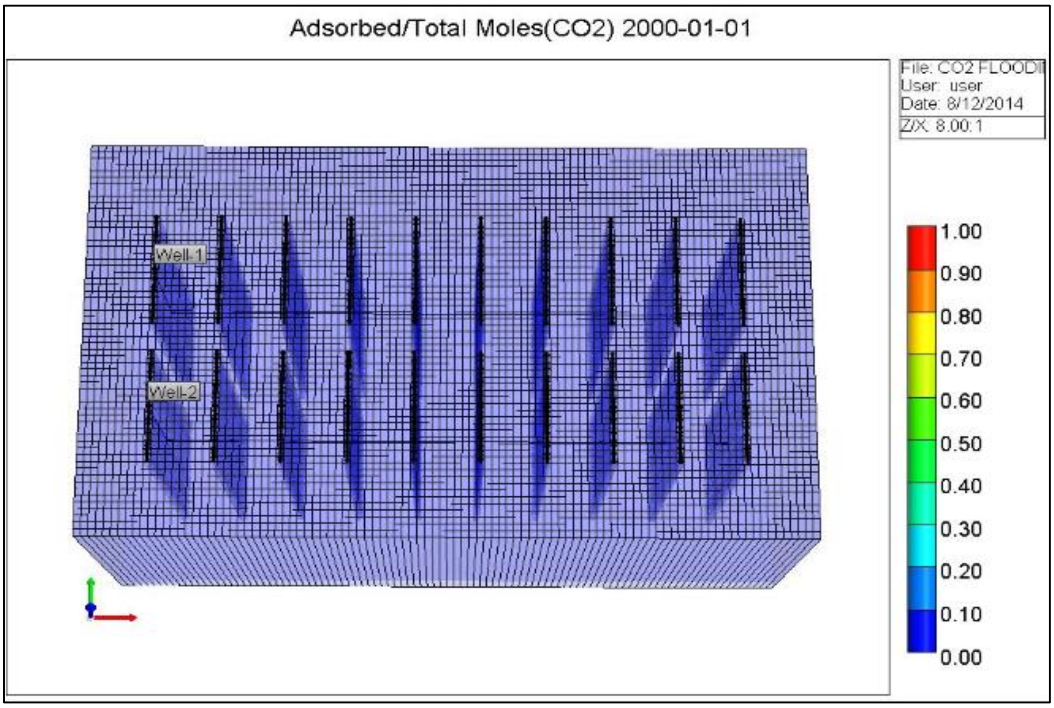


Figure 20 : Shale matrix CO_2 moles distribution before production and injection

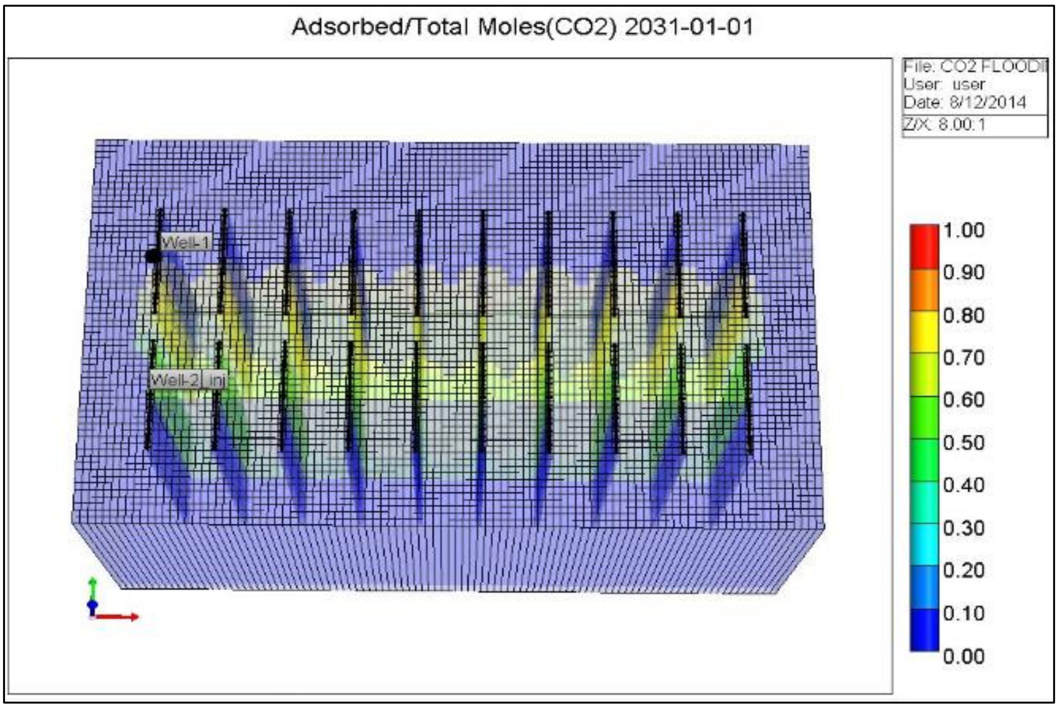


Figure 21: Shale matrix CO_2 moles distribution after 30 years of production and 5 years of CO_2 flooding

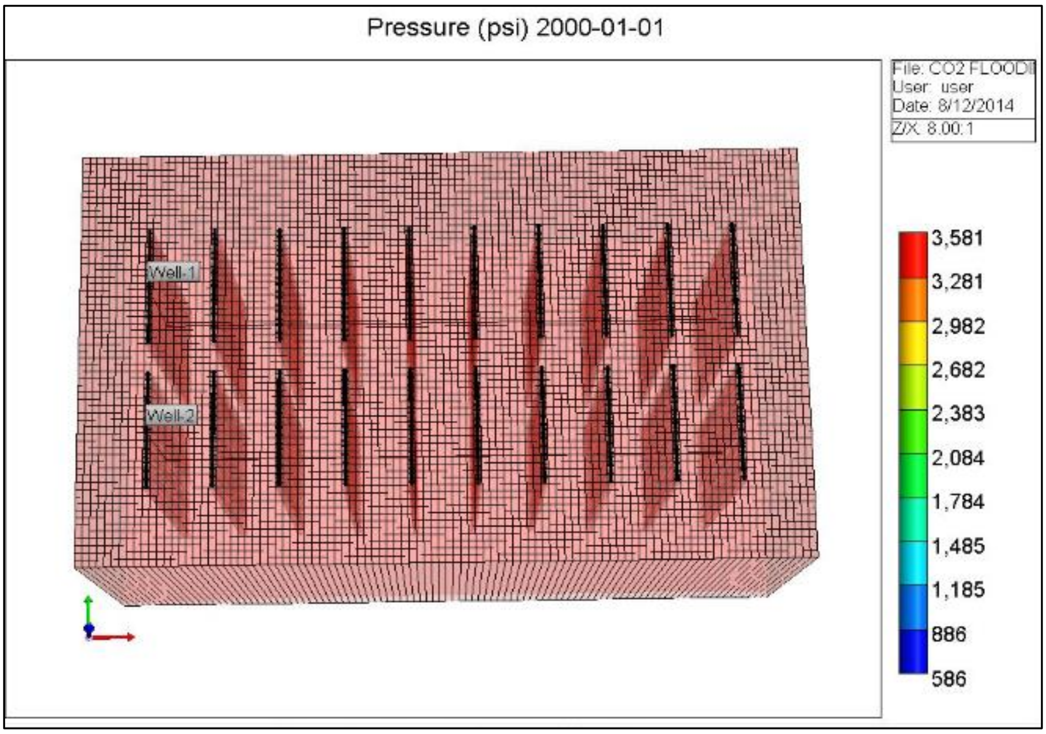


Figure 22 : Shale matrix pressure distribution in the reservoir before production.

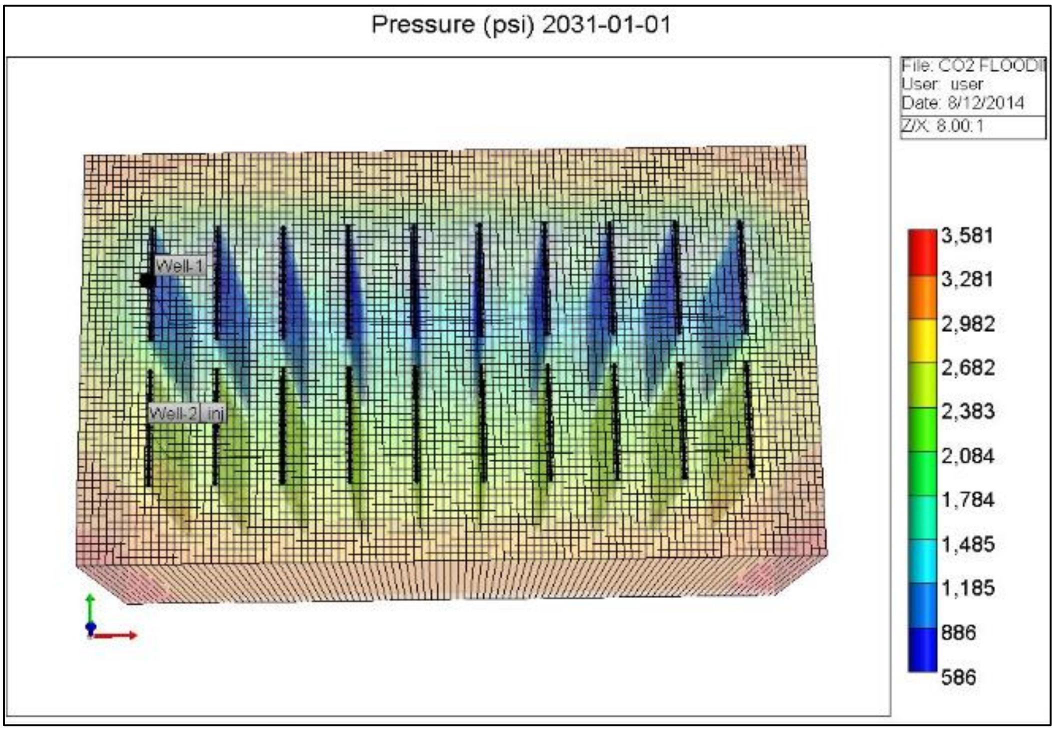


Figure 23 : Shale matrix pressure distribution in the reservoir after 30 years of production and five years of CO_2 flooding.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

As conclusion, the feasibility study for enhanced shale gas using carbon dioxide is explored in this study. Adsorption of CO_2 and CH_4 are study to evaluate the mechanism of gas recovery in shale. A basic model of shale gas based on data from previous research is simulated to analyse the case with and without CO_2 flooding scenario as well as considering the adsorption. CO_2 early breakthrough and cumulative gas production are explored and compared. The conclusions are as follows:

- CO_2 adsorption match with BET isotherm curve and CH_4 match with Langmuir isotherm. As the pore pressure increase, the adsorption capacity increase. In order to desorb the CH_4 from shale matrix, a very low pore pressure is needed or injection of CO_2 as it is most preferable to adsorb (6 to 10 times) than CH_4. The adsorption give impact to the total gas in place about 4% to 12% increment.
- CO_2 injection has potential in enhanced shale gas recovery. The best option of CO_2 injection modes is CO_2 flooding as it enhances gas recovery by 1.83%. Whereas CO_2 huff-n-puff gives negative result about 1.7% decrement in shale gas recovery. CO_2 huff-n-puff also reproduce CO_2 quickly to the surface.
- By considering injection, the cumulative gas production increase and the average pressure deplete slowly. The effect of repressurizing due to CO2 flooding enhanced shale gas recovery.

5.2 Recommendations

For future works, there are a few suggestions that should be taken into consideration to improve the evaluation of the CO_2 injection in shale gas. The real field data such as production data from shale gas need to use for simulation and history matching to understand the behaviour of shale reservoir and evaluate the potential of CO_2 injection. The second recommendation is conducting experimental work to analyse and evaluation the impact of CO_2 injection by using the core sample. Further economics evaluation also need to consider.

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