The Effects of Reservoir Temperature on Carbon Dioxide (CO_2) and Nitrogen (N_2) Gas Sorption in Enhanced Coal Bed Methane (ECBM) Production

By

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Hardbound Report submitted in partial fulfilment
of the requirements for the Bachelor of
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CERTIFICATION OF APPROVAL

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A dissertation report submitted to the
Petroleum Engineering Department of
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in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
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Approved by,

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MAY 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.

ALISTER ALBERT ANAK SUGGUST

ACKNOWLEDGEMENT

In completion of this Final year project, I would like to express my deepest gratitude to all parties that involved in making this project as a meaningful and great achievement for me. Throughout the project timeframe, I have learned a lot of new things and gained so much experience that will be a huge value for me in the future.

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Finally, my deepest appreciation goes to my family and my friends in UTP for their continuous support and encouragement which have enabled me to do my best for this project. I hope after this project has completed, all the findings and knowledge that I have shared through this report would be useful for everyone in the study field.

ABSTRACT

Recently, the enhanced coal bed methane (ECBM) production has become the interest of many researchers especially for those who are related to the industry of energy. Over the years, the implementation of this method has been able to stimulate the production of coal seams and able to unlock the potential of gaining the more hydrocarbon gas from the coal bed body. Many studies been done in relation to investigate on few factors that may affect the efficiency of the carbon dioxide (CO_2) and nitrogen (N_2) gases injection into the coal seams for better understanding on the method. One of the trends of study which is becoming the backbone this report is to understand on how does the temperature effects on the sorption behavior of CO_2 and N_2 with methane (CH_4) gas at different reservoir temperatures, as sorption is a physical process which can be easily altered by the physical changes of the system. To answer this question, this report will present on the reservoir simulation study on the efficiency of CO_2 and N_2 to displace CH_4 in the coal seam at different reservoir temperatures. In order to accomplish the objectives of the study, the study will be involving reservoir simulation on the production of ECBM at different coal bed reservoir temperature by using CMG's GEM reservoir simulator. The report resulted in the comparison of the maximum adsorption capacity, rate of adsorption and the flood front shape of the ECBM of different gases at different reservoir temperature.

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CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
ECBM	Enhanced coal bed methane
EPA	Environmental Protection Agency
N_2	Nitrogen
P	Pressure
P_L	Langmuir volume
V_L	Langmuir pressure

CHAPTER 1

INTRODUCTION

1.1 Background

All around the globe, coal bed methane (CBM) has been recognized as one of the major prospect of unconventional hydrocarbon sources. CBM, as suggested by its name is the hydrocarbon which is found in the body of coal seams and contain a vast amount of natural gas, methane (CH_4). The coal bed contain two (2) types of porosity systems of the cleats and the matrix. As a mean of storage, most of the methane gas is adsorbed on the coal surface and being retained hydrostatically due to the aquifer pressure acting on the coal seam (Dunn, 1989). The methane will only be desorbed from the coal surface after the pressure of the aquifer drops. The desorbed methane will flow along the cleat system to the wellbore to be produced to the surface. The understanding towards the CBM storage and permeability system leads us to the discovery of the methods to enhance the production of the well.

The injection of carbon dioxide (CO_2) and nitrogen gas (N_2) gas into the coal seam is one of the common methods of performing the enhanced coal bed methane (ECBM) production. The injection CO_2 or N_2 gas into the coal bed reservoir will aid the extraction of the initially in place CH_4 from the reservoir by partial pressure reduction and sorption process. The study will be fully focusing on the how does the sorption behaviour varies in different reservoir temperature. In the sorption process, the injected gas is used to occupy the porous space and to substitute the CH_4 via the two-way traffics of sorption process

(Seidle, 2011). The two-way process involved the adsorption of the injected gas onto the coal surface and the desorption of the CH_4 from the coal surface.

As we all know, the different types of gases of CO_2, N_2 and CH_4 have numerous distinctive differences especially in terms of their critical properties. Due to this, many studies have been done to investigate on the effects of few aspects on the sorption behaviour of CO_2 and N_2 with CH_4 on the coal body in order to understand on the subsurface process during ECBM. One of the critical properties of these gases to be compared about is the temperature which is generally known to effect the physical reaction to be studied; sorption process.

1.2 Problem Statement

Enhanced Coal bed Methane (ECBM) production by gas injection is known to be one of the most common methods in stimulating the production of CBM fields. The main focus of the topic is to study on the effect of the reservoir temperature on the gas capacity content of the coal bed and its sorption behavior. As we all know, coal bed body acts as a sorbate to the adsorbed gas via physisorption mechanism (physical adsorption), which can be easily effected by the surrounding physical changes like pressure and temperature. Based on the understanding on Langmuir equation, the adsorption capacity of gases onto coal bed can be predicted with ease. However, there is not many studied to relate the effect of reservoir temperature on the physical sorption process of the coal bed.

The study will resulted on which injected gas is more favorable to be adsorbed on coal bed at different reservoir temperature, the rate of sorption of injection gas-initial gas in place and the rate of production of coal bed methane. A thorough simulation need to be conducted in order to understand more on the sorption behavior of on the coal bed at various reservoir temperature.

1.3 Objectives and Scopes of Study

The objectives of the project are as follows:

i. To perform simulation on the effects of coal bed reservoir temperature on CO_2-ECBM and N_2-ECBM production

ii. To compare on the reservoir temperature effects on CO_2-ECBM and N_2-ECBM production

1.4 Scope of study

The main focus of this project is to study on carbon dioxide (CO_2) and nitrogen (N_2) gas sorption behavior and the CBM preferability of the adsorbate under different reservoir temperature. The scopes of study will include a reservoir simulation study using CMG's GEM software involving the sorption behavior of CO_2, N_2 and CH_4 under the influence of different reservoir temperature in ECBM. The study is feasible to be done with adequate tools in the campus and set to be completed in the given time frame of FYP I and FYP II. The study is hoped to improve the understanding on the CO_2 and N_2 injection in coal bed and CBM production technology.

CHAPTER 2

LITERATURE REVIEW AND THEORY

In the literature review and theory chapter, the author will unfold on the literature review analysis and the theory that serve as the backbone of the study. This chapter is divided into four (4) subsections which will explain on the crucial information that leads to the effort of proposing the title of the project.

2.1 Coal formation

Coal bed methane (CBM) or coal seam gas (CSG) is rooted by a keyword of coal, which is the integral subject to be understand about before proceeding to apprehension of the much complex CBM reservoir system. Coal rock is defined as a combustible black or dark brown rock sedimentary rock mainly consisting of carbonized plant matter which is found mainly in underground deposits and widely used as fuel. According to Strickland (2008), coal is a sedimentary rock composed of carbon, hydrogen, oxygen, nitrogen, sulfur and various trace of elements while it is also containing carbonaceous content of 50%-70% by volume of coal.

Coal is basically formed by a process called coalification, the progressive changes in composition and structure of the sedimentary organic matter throughout its burial history (Levine, J. R., 1993). Coalification is a digenetic alteration of the sedimentary organic matter which is also a combined process of physical, chemical and biological alteration of the organic matter.

Prior to the coalification, the organic matter will undergone peatification which in result will produce peat. Anderson et al (2003) stated that peatification is a continuous subaqueous deposition of plant-derived organic matter in environment of oxygen-poor interstitial water like deltaic or marginal marine environment. Then, coalification process took place after the peatification to convert the peat into coal. The coalification process is initiated by biochemical degradation, followed by continuous increasing overburden pressure and subsurface reservoir temperature as the peat is buried over time. As the coal is becoming harder and blacker, its forms the bituminous or hard coal which is then classified into ranks according to its maturity.

The ranks of coals are arranged in increasing order of its alteration and maturity, which suggests that the high ranked coal have lesser amount of fluid content of water, carbon dioxide and methane due to the impact of squeezing. The coal physical parameters which clearly defined the ranks are the moisture, volatile content and carbon content. The cleanliness and the carbon contain of the coal is increasing as we go from the low rank coal to the high rank coal (Lignite, sub-bituminous, bituminous and anthracite) (Laubach et al, 1997). The figure in Appendix I shows the increasing rank of coal from left to right.

2.2 Coal bed storage system

Coal bed methane (CBM) refers to the form of primary coal seam gas which can be produced from coal beds. Coal-bed is generally known as an unconventional gas reservoir. Coal-bed is composed of altered vegetative material - macerals, which serve the purpose of being both as the hydrocarbon source and reservoir (Anderson et al, 2007). Coal is a heterogeneous and anisotropic porous media which is characterized by two distinct porosity systems; simply recognized as dual-porosity system of micropores and macropores. The macropores or the cleats are composed of the parallel natural fractures in the coal bed. The micropores, or the matrix, work as to contain the vast amount of gas in the coal bed. In this project, it is important to develop thorough understanding on the storage system of CBM reservoir system since it is the media for the adsorption, so called sorbent (Aminian, 2007).

The flows of fluids in the coal bed to the wellbore in CBM reservoirs are channeled by the natural fracture system (Aminian, 2006). These natural fractures are the aforementioned macropores or commonly known as cleats. The macropores are consisting of two sets of mutually perpendicular fractures, both of which are perpendicular to the bedding plane.

The rife set of common parallel and extensive fractures are termed as face cleats while the less well developed and terminating at face cleats are known as butt cleats (Seidle, 2011). These bedding plane-aligned natural fractures resulted in an anisotropic behavior of the coal bed.

The cleats are initially saturated with water while the gases are stored in the micropores of the coal body. Due to this condition, the production of gas from the coal bed methane requires the process of dewatering. The dewatering process works by decreasing the reservoir pressure to initiate the desorption of gas to the surface of micropores and into the cleats channels (Ismail, 2005).

Aminian (2007) and Seidle (2011) suggested the gas storage capacity of coal is related to the pressure via the relationship called the sorption isotherm concept. The adsorption model, which becomes the basis of the storage mechanism in coalbed, is usually described with Langmuir's equation:

$$V = V_L \frac{p}{p + p_L}\text{; where}$$

V = gas content, scf/ton or cm3/g

V_L = Langmuir volume constant, scf/ton or cm3/g,

p = Pressure, psia or MPa

p_L = Langmuir pressure constant, psia or MPa

In the field of studies related to the sorption behavior of the gas in CBM reservoir under various conditions, it is denoted that the equation is always being commonly used to compare with the actual experimental result gained (Pini et al, 2009, Busch & Gentersblum, 2011, Siemons & Busch, 2006, Busch et al, 2004, Charrière et. al., 2008, Zhang et al, 2011). The reason behind of the preference is due to the accuracy of Langmuir's equation to account the microporous sorption behavior when sorbent pore dimensions and gas molecules sizes are compatible (Seidle, 2011).

The storage mechanism of methane in coal bed can be explained by the understanding on the physical adsorption on microporous solids. Adsorption refers to the process of accumulation of fluids on the surface of solid or liquid to form a molecular or atomic film

(Kumar, 2009). The sorption storage mechanism phenomena is a direct result of the acting van der Waal's forces between the methane-coal surfaces and methane-methane molecules, in which the forces between gas-solid is much superior (Rogers, 2012). 98% of gas within the coal bed is being stored by this mechanism, in which depends on the pressure at which the gas is being adsorbed, while the other 2% is stored in the pore or cleat space (Gray, 1987).

The adsorbed methane gas will retained on the coal surface due to the presence of water in the coal bed that will create a hydraulic pressure to contain the methane from being desorbed from the coal surfaces (Dunn, 1989). In order to produce the methane from the coal seam, the methane gas must be desorbed from the sorption area or within the coal matrix before it diffuses to the cleat system. The methane will travel along the natural fracture or the cleat systems till it reaches the wellbore (Edward, P & Palmer, I., 1996).

2.3 Gas Injection Mechanism in Enhanced Coal Bed Methane Production (ECBM)

Coal bed methane initial production is usually done by utilizing the primary depletion recovery method. In the initial production, the reservoir pressure of the coal is lowered by the water production from the coal bed. The production of water leads to the reduction of the hydraulic pressure which retained the methane on the coal surfaces and reducing the partial pressure of the methane from the sorption site. The detailed plot of coal bed methane production is shown in Appendix II. The methane will get desorbed from the sorption site and move outwards to the cleats and flows to the wellbore. As the methane is continually produced, the reservoir pressure and the recovery rate will deplete along with time (Edward, P & Palmer, I, 1996, Dunn, 1989).

Due to the depletion recovery rate, enhanced coal bed methane recovery methods are introduced in order to recover more methane from the coal bed. Gas injection is one of the alternatives in ECBM. The first simulation on gas injection - ECBM is done by Collings who had resulted to the change in industry to focus on the effort to improve on the commercial ECBM simulators (Collings, 1982).

Puri and Yee (1990) reported that the adsorption capacity of coal depend on the component type and the partial pressure of the gas phase; depend on the concentration of gas phase, as shown in the figure below. The findings suggested that by injecting inert gas into the coal bed, the gas will be adsorbed onto the sorption site and then increases its partial pressure in the coal bed, thus maintaining the total pressure. On the other hand, as the partial pressure of methane is then reduced, methane is then desorbed from the coal bed and disperse into the cleat systems. It was also suggested the usage of nitrogen gas, N_2 as the injection gas in the ECBM phase because they are cheap and abundant, plus, be able to work similar to the tested inert gas, the helium gas, He_2 (Puri and Yee, 1990).

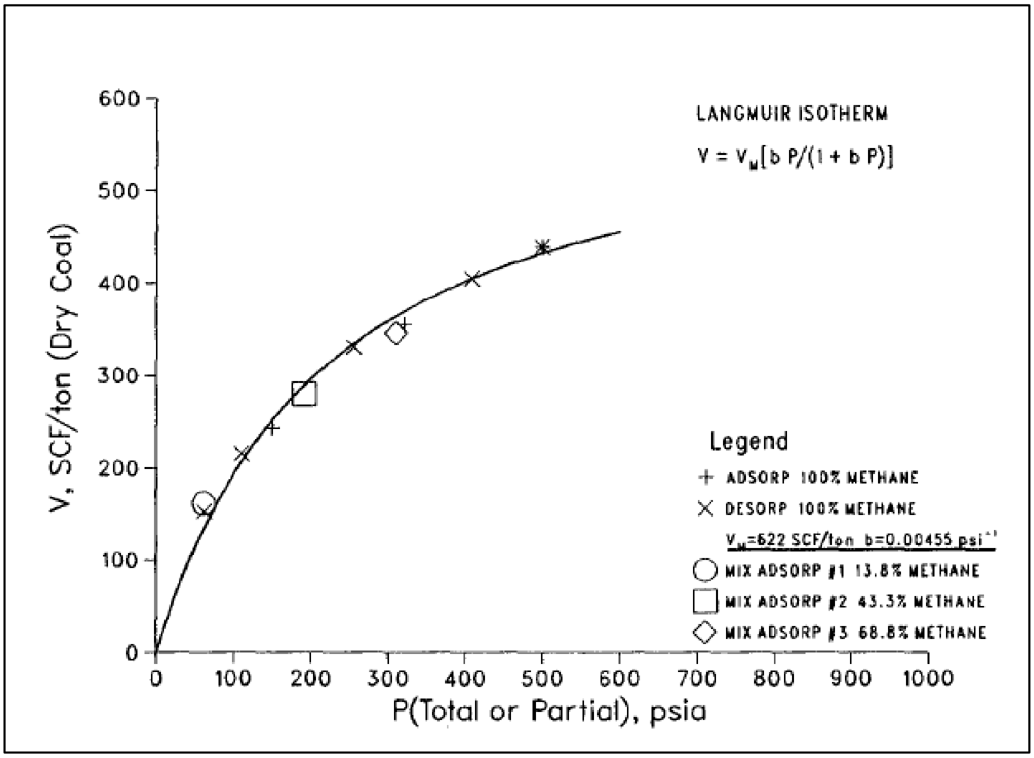

Figure 2. 1: The sorption capacity of dry coal is increasing at increasing concentration of methane. This proves that the partial pressure of injected gas is important in gas sorption mechanism. (Puri & Yee, 1990).

Despite of the ability of N_2 to release the adsorbed methane from the coal by both sorption displacement and partial pressure reduction, Puri and Stein (1988) and Puri and Yee (1990) also found that the coal has lower sorption affinity towards inert gases, as shown in the figure below. The low affinity towards inert gases such as N_2 lead to the early gas breakthrough during ECBM. This is because inert gases tend to flood the coal deposit rapidly with minimal loss to the coal.

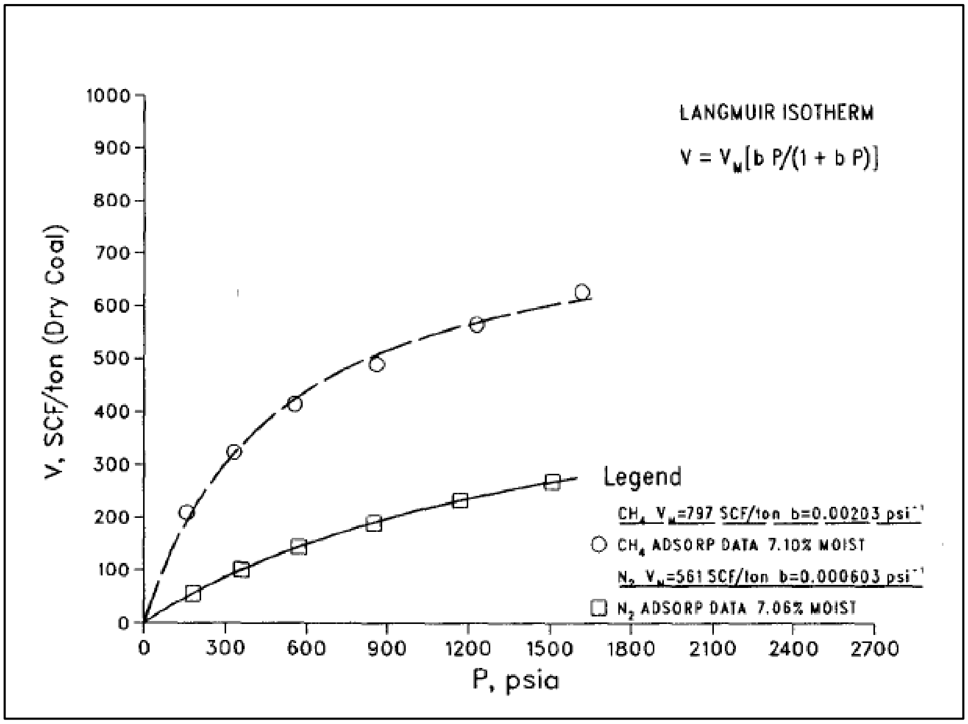

Figure 2. 2: The coal has lower affinity towards inert gas adsorption. The graph shows that more methane has been adsorbed onto coal than nitrogen at any given pressure. (Puri & Yee, 1990)

Reznik et al (1982) reported that CO2 injection can also be used to enhance the recovery of the coal bed methane. The sorption process in ECBM via CO_2 injection involves a two-way traffic exchange process involving the adsorption of CO_2 and desorption of CH_4 at the matrix space. Different from the N_2, CO_2 is proven to have higher affinity for coal than CH4, thus establishing a competitive adsorption process on the sorption site. The injected CO_2 will displaces the methane from the sorption site, thereby making the desorbed methane to be free to disperse into the cleats and flow to the wellbore. However, Puri and Stein (1988) reported that this method requires huge amount of CO_2 to be injected into the coal seam in for the CO_2-CH_4 sorption exchanges to occur.

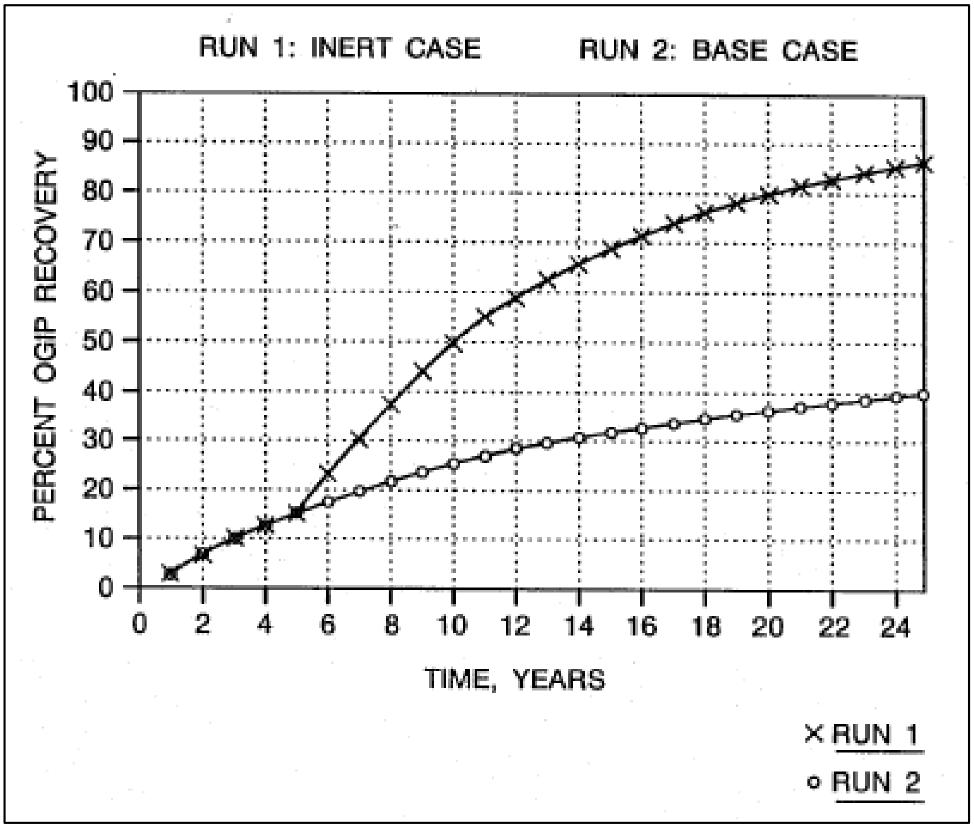

Figure 2. 3: The effects of nitrogen injection on methane recovery study by Puri and Stein (1988)

As explained by Seidle (2011), the CO_2 tend to be adsorbed more strongly than methane by the coal, thus creating a slow-moving flood to sweep the methane into the production flow. Due to this issue, CO2 injection should be considered in ECBM due to the economical issues especially in dealing with small reserves CBM. The affinity of coal towards CO_2, however, leads to the slow breakthrough compared to the inert gases since it is adsorbed to the micropores (Reeves, 2002). Another concern on CO_2 preferability in ECBM is because of the benefits of performing the CO_2 sequestration; the CO_2 from carbon capture and storage (CCS) is safely stored in the reservoir, thus reducing the greenhouse gas emission (EPA.GOV, 2014).

2.4 Effects of reservoir temperatures on CO_2 and N_2 Injection in Enhanced Coal Bed Methane (ECBM)

Throughout the years, numerous studies on injected gas sorption in coal bed has been done, in relation to the aspects like the permeability, porosity, coal rank, coal density, ash and moisture content, gas sorption capacity, pressure, temperature and the gas diffusivities (Busch and Gensterblum, 2011). However, there is not much study on the effect of temperature on CO_2-ECBM and N_2-ECBM injection even though Pashin and McIntyre (2003) suggested that the process of gas sorption on coal is sensitive to pressure and temperature.

The effect of temperature on sorption behavior in ECBM should be studied as the reservoir temperature for coal seam is generally known to be ranges from 80˚F to 125˚F (27˚C – 51˚C) as reported by Pashin and McIntyre (2003). The sorption capacity of coal is sensitive to temperature and can vary significantly in coal bed methane reservoirs (Pashin et. Al, 1991). Based on the suggested reservoir pressure range, it is known the temperature also includes the critical temperature of CO_2 gas, which has the critical point at the temperature of 88 °F (31 °C) and the pressure of pressure of 1074 psia (73 atm); which is within known reservoir conditions. On the other hand, methane gas critical point is known to be at the temperature of -116 °F (-82.3 °C) and the pressure of 672 psia (46 atm).

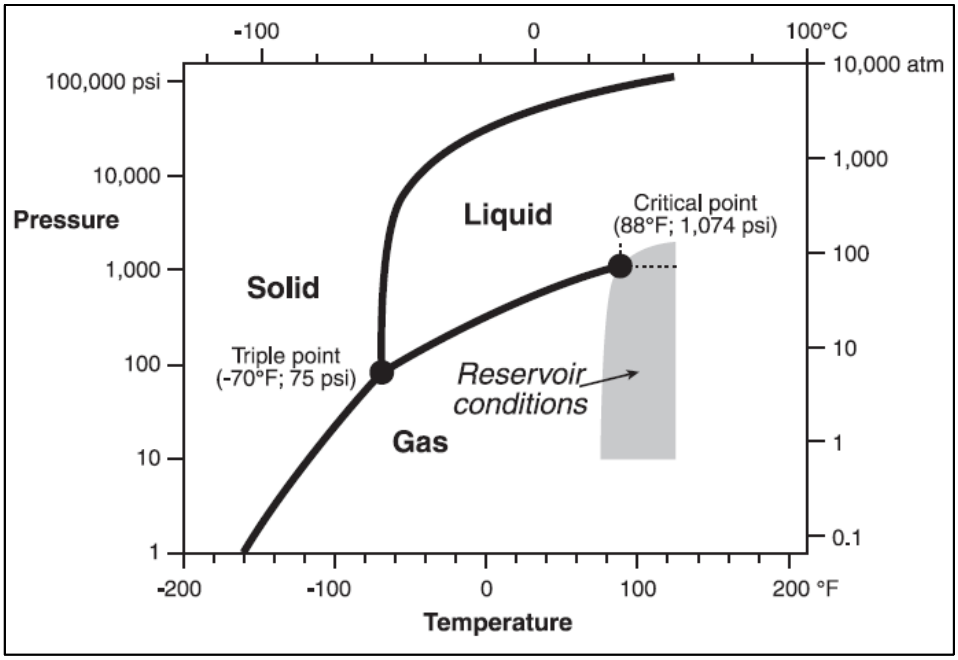

Figure 2. 4: Phase diagram for CO_2 showing relationship of the critical point to temperature-pressure conditions in coalbed methane reservoirs of the Black Warrior basin. Based on general pressure gradient inclination, the CO_2 is known to be released into its supercritical phase at the stated condition.

Critical point is the condition at which no phase boundaries exist, which may suggested that the supercritical fluid to expand like gas to fill its container but with the density of its liquid phase. Kroos et al. (2001) reported that coal have higher capacity to hold CO_2 under supercritical condition but there is not prove on the stability of the supercritical CO_2 in the coal seams. Pashin and McIntyre (2003) later confirmed that coal can actually adsorb huge quantities of supercritical CO_2, but further research need to be done to determine the mobility and the reactivity of the supercritical fluid.

The study on the dependency of sorption rate on temperature by Busch et. al. (2004) discovered that the injected gases adsorbed and reached pressure equilibrium faster at higher temperature. A simple experiment is conducted during the study by having an increase of 13˚ C temperature differences, in which resulted a double rate f adsorption to pressure equilibrium (Busch et al., 2004).

Zhang et al (2011) conducted a laboratory experiment to study on the influence of the temperature on the gas content and sorption modelling of CO_2 on coal samples. Apart from that, the study also found that gas is adsorbed faster onto the coal sample at high temperature. The high rate adsorption process is because at high temperature, the gas gained high molecule energy that it can readily reach the adsorption position (Zhang et al, 2011). Zhang et el also managed to compare the experiment result with the Langmuir model and found that the Langmuir volume gap of the trend line is larger at lower temperature compared to higher temperature.

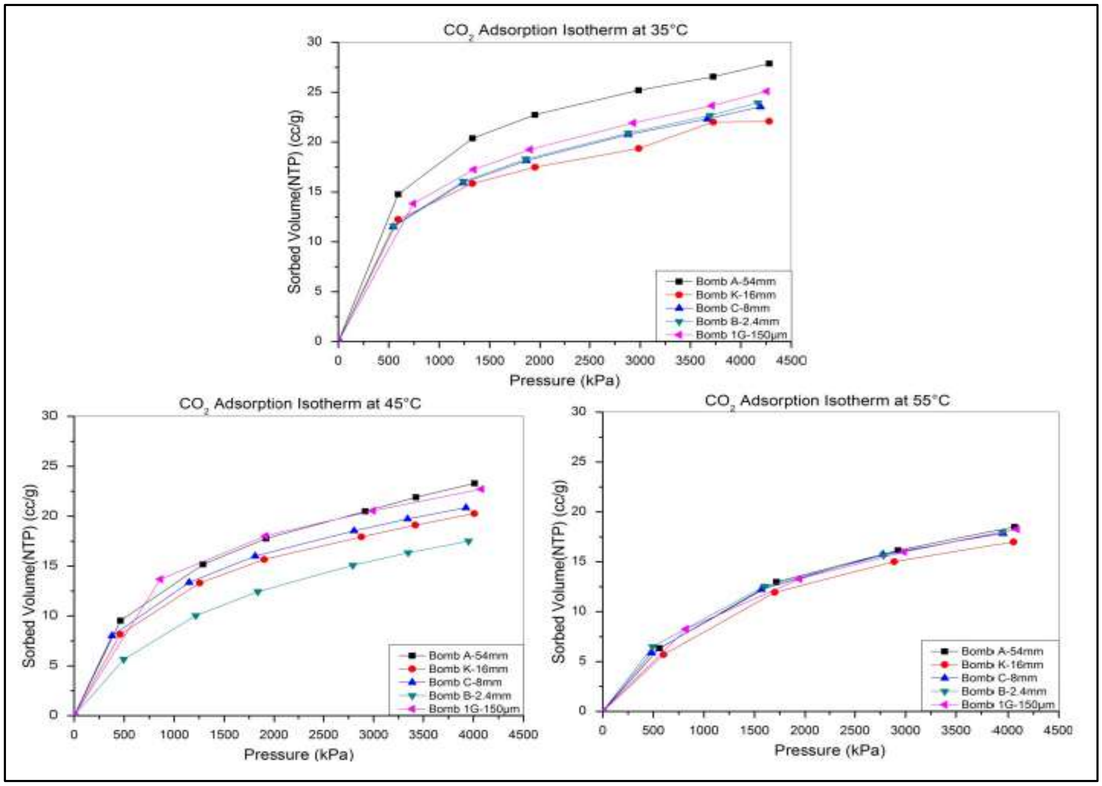

Figure 2. 5: The sorbed volume of CO2 gas at three (3) different temperature. (Zhang et al, 2011)

Seidle (2011) highlighted that that the maximum sorption capacity of coal on gases decreases as the temperature increase, which is also the similar findings made in the earlier studies by Bae and Bhatia (2006), Sakurovs et al (2008) and Pini et al (2009). The plot of sorption capacity and the expected Langmuir isotherm capacity of temperatures that ranges from 33 ˚C to 60 ˚C can be seen in Figure 2. 6. These experimental findings are actually different to the assumption of Langmuir sorption isotherm which denoted that the sorption capacity is only a function of temperature. The contrary is explained by the utilization of different mechanism in the experiment compared to the suggested Langmuir model which is only suitable for adsorption mechanism (Seidle, 2011).

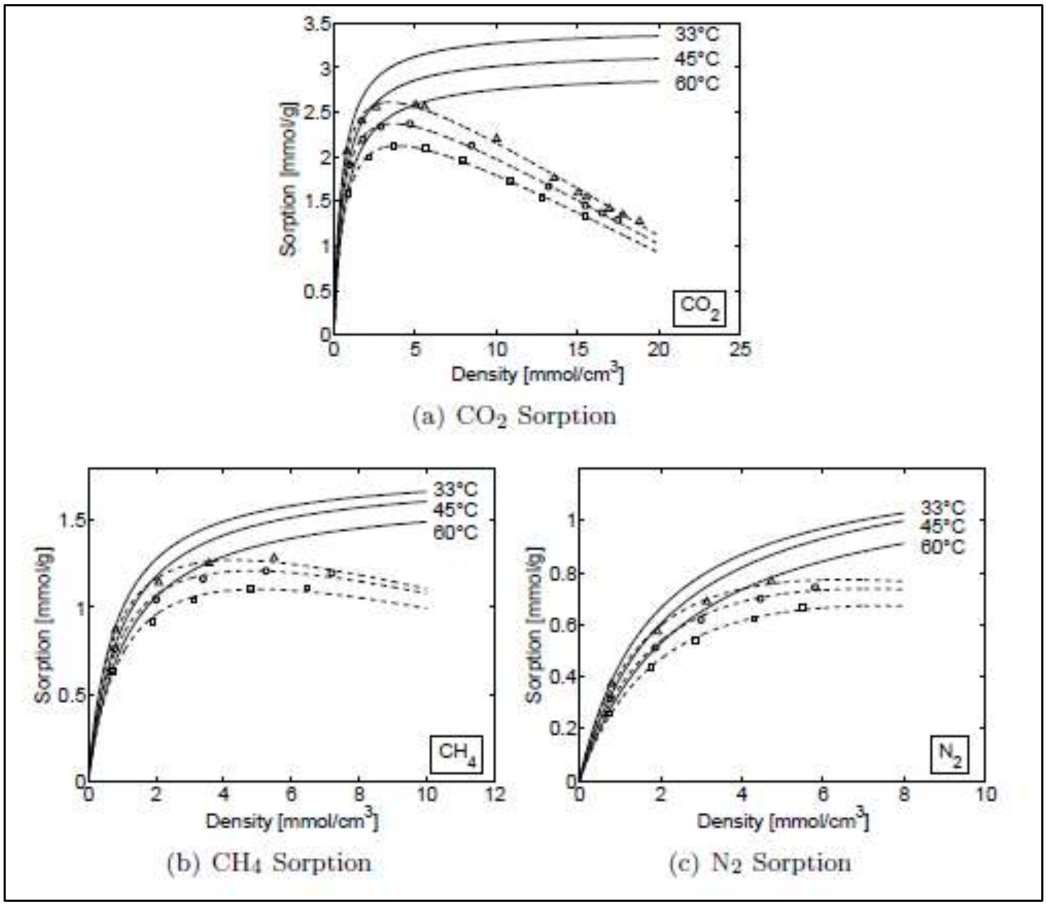

Figure 2. 6: The molar excess sorption of CO_2, N_2 and CH_4 on coal sample at 3 different temperatures, namely 33 ˚C, 45 ˚C and 60 ˚C, for experimental and models result. (Seidle, 2011)

Li et al (2009) conducted a study on CO_2 isotherm sorption and found that the high pressures CO_2 sorption capacities are sensitive to temperature changes and at low pressure, the sorption capacities is not affected by the temperature changes. The same study also found that the temperature affects CO_2 sorption capacities differently in low and high pressure condition. At intermediate pressure, Sakurovs et al (2007) found that the sorption capacity of coals for CO_2 is reduced with inclining temperature. Li et al (2009) also found that the maximum CO_2 sorption capacities of coal degraded with inclining temperature, in which the dependency on temperature is also relies on the coal ranks.

Along the year, there are many completed studies on the effect of temperature on the sorption of CO_2 in coal seam compare to the studies related to N_2. The difference of number of studies implied that the industry has more interest in investigating of CO_2 utilization compare to N_2 in ECBM recovery. Plus, it is generally known that coal has higher affinity to adsorb CO_2 compared to N_2, implying that further understanding on CO_2 adsorption process is more needed than N_2.

It is concluded that based on the literature study, it is denoted that the temperature do affects the sorption of CO_2 and N_2 in ECBM production.

CHAPTER 3

METHODOLOGY

For the purpose of this project, the experiment part will be completed with the CMG's GEM Simulation Software for the ECBM production at different reservoir temperature simulation study. The flowchart below gives the general idea on the flow of activities for the study.

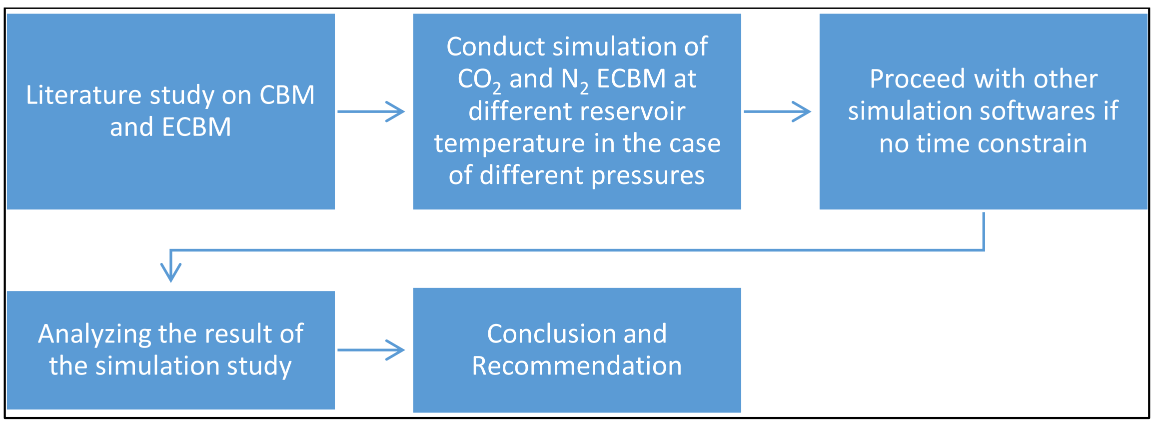

Figure 3. 1: The summary of planned methodology for the study.

The methodology of the project is discussed as follows.

3.1 Tools and equipment

The tools and equipment for this project is divided into two (2) parts which are the lab equipment and the simulation software.

3.1.1 CMG's GEM Simulation Software

For this study, GEM is main simulation software to be used for the ECBM simulation work. GEM can model tertiary recovery processes and used extensively for coal bed methane (CBM & E-CBM) and CO_2 processes. The software will be utilized to simulate the production behavior of coal bed with the assist of CO_2 and N_2 injection under different reservoir temperature. (CMG Website, 2014). The data file for the CBM is also attached in the Appendix IV. The same data file was being used for similar work by Saugier (2003).

3.1.2 Schlumberger's ECLIPSE- E300 Simulation software

Backup software for GEM. The simulation software can be utilized to simulate the production behaviour with the assist of CO2 and N2 injection at different temperature. According to Mora (2007), the simulator is able to model the sorption, coal shrinkage, compaction effect and under-saturated coals due to its dual porosity models.

3.2 Flow Chart

The flow chart for the work methodology for the study is as per shown below.

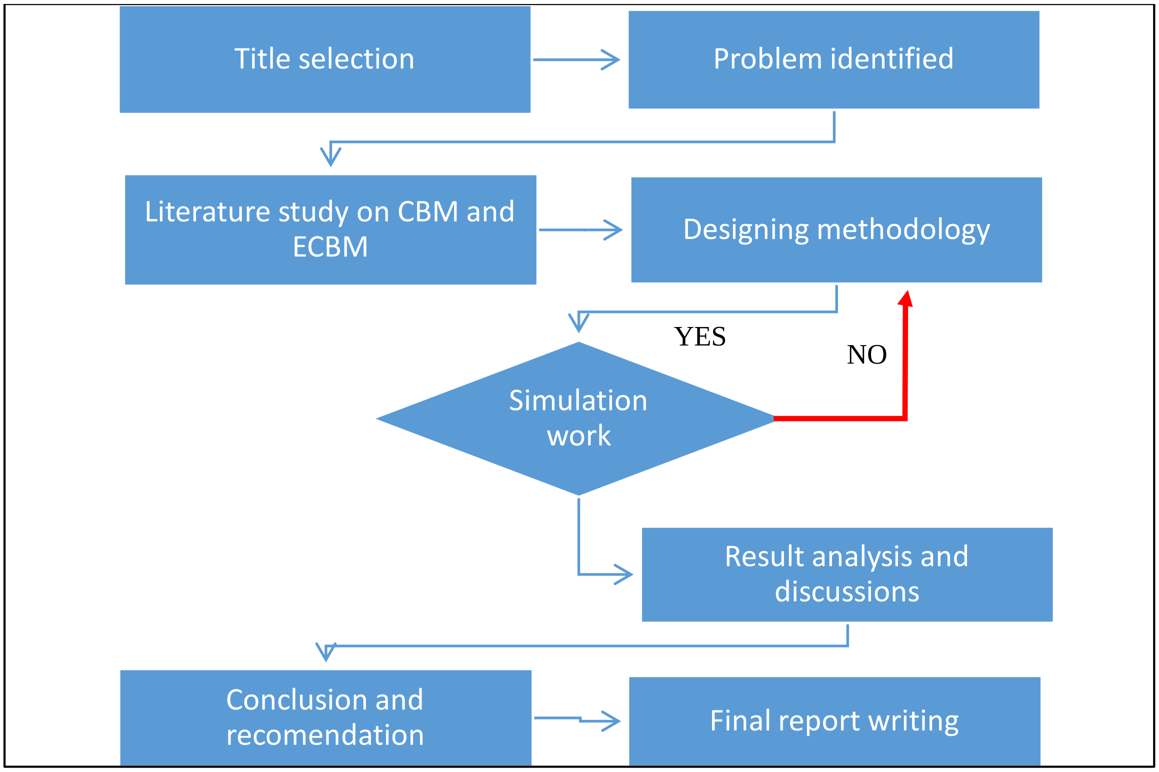

Figure 3. 2: The flow chart of methodology work. In case of any failure or difficulties in working on with the experimental work or simulation work, the author need to come back to designing methodology stage to redesign the activities.

The flow chart for the simulation software is shown as per below.

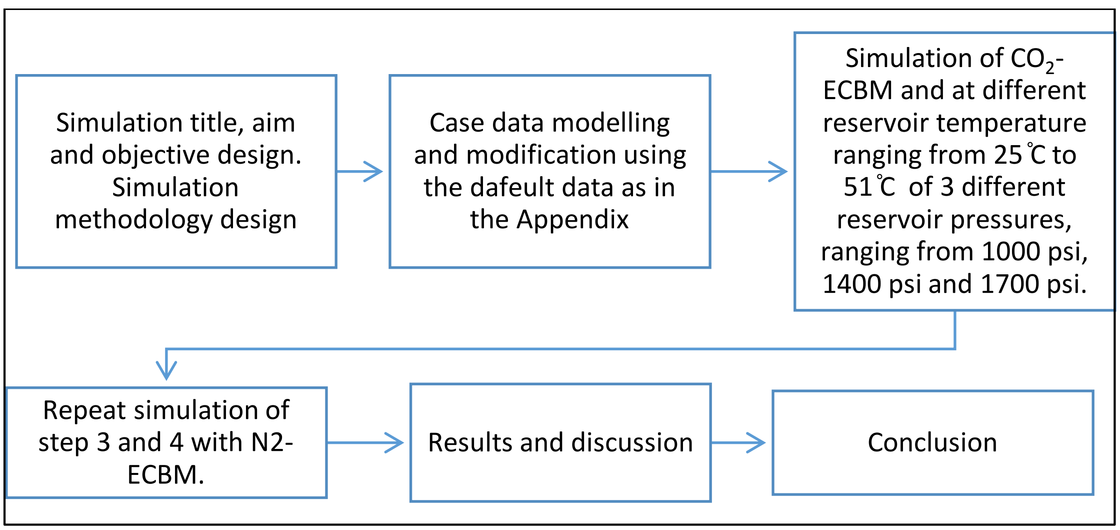

Figure 3. 3: The flow chart for the simulation works. In the simulation, the coal ranks and pressures will also be varied as these properties will affect the intensity of the reservoir temperature effects, as the function of coal moisture and sorption capacity, respectively.

3.3 Project Milestones

The key milestones that has been completed for the study till date is as per follows:

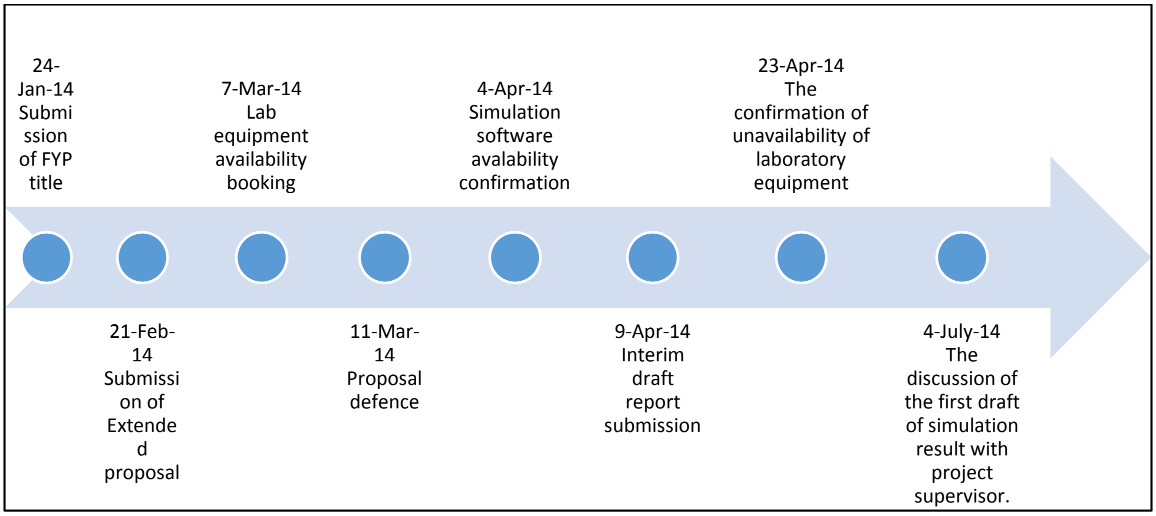

Figure 3. 4: The key milestone for the completed activities till date

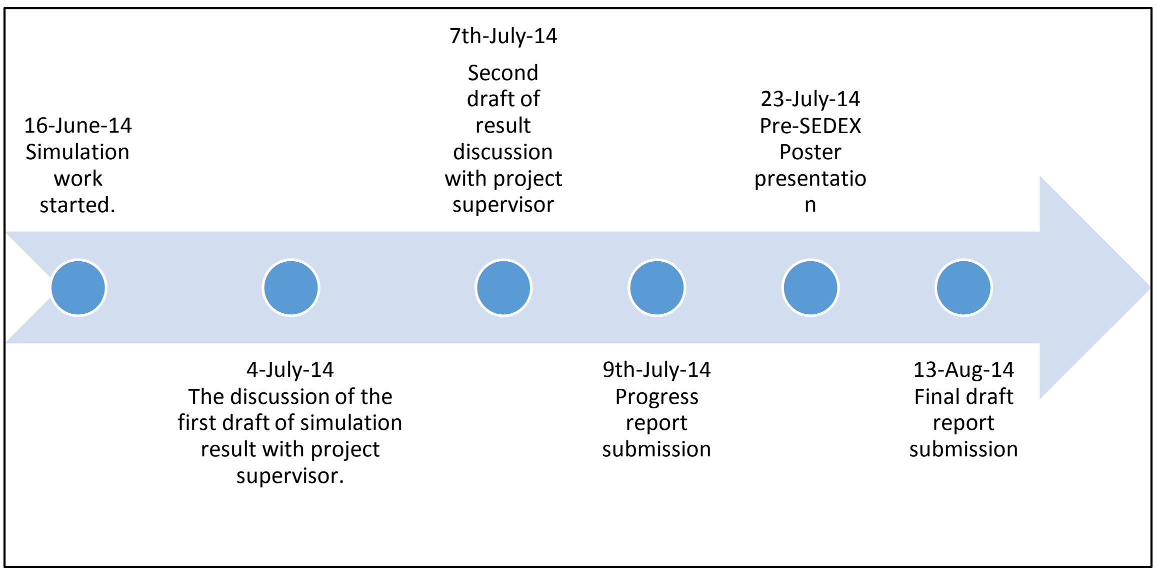

Figure 3. 5: The key milestones for FYP II Progress.

3.4 Project timeline/Gantt chart completion

Focusing on the time frame of FYP I, it is denoted that most of the targeted activities has been completed. For FYP I, most of the project activities would be the literature studies and the designing methodology of the experimental and simulation works.

Table 3. 1: The Gantt chart of FYP 1 and FYP 2.

	Task/ Activities	**Week**													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
FYP1	Selection of Project Topic														
	Preliminary Research Work														
	Submission of Extended Proposal														
	Proposal Defence														
	Project work continues														
	Submission of Interim Draft Report														
	Submission of Interim Report														
FYP 2	Case data modelling														
	Simulation study														
	Progress report submission														
	Pre-SEDEX														
	Submission of draft final report														
	Submission of soft bound dissertation														
	Submission of Technical paper														
	Viva														
	Submission of hardbound Project Dissertation														
Legend	Completed last sem														
	Current progress														
	Planned progress														

3.5 Case Data Model for Simulation

For the simulation study, the base case model is taken from the CMG GEM case data entitled ECBM Problem. The reservoir is being represented by a layer of grid blocks with the dimension of 25 x 25 and is placed with two (2) wells for the mean of injection and producing. The reservoir contained two (2) phase of fluid which are the 198.61 MM scf of methane gas initially in place and an underground aquifer. The ECBM process gas injection for the case study started after three (3) months of primary recovery for all the cases with the maximum rate of 6000 STD m^3/D or 2.12×10^5 scf/D. The figure below shows the 3D projection view of the reservoir grid blocks and the well positioning.

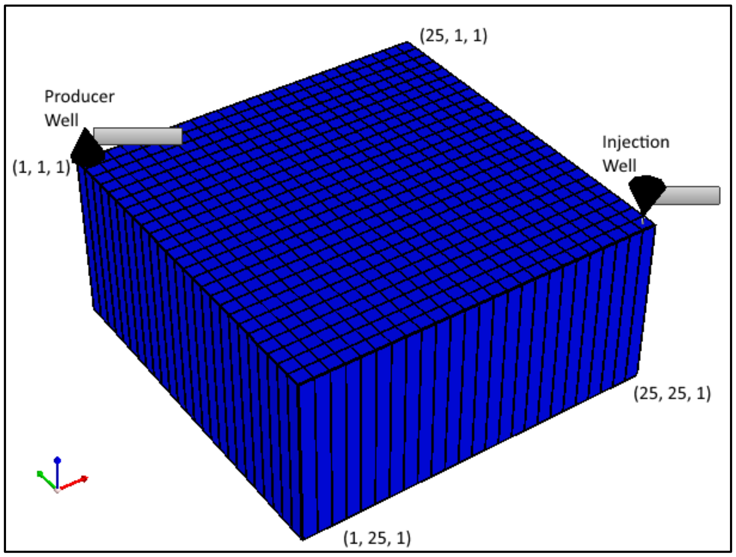

Figure 3. 6: The 3D Projection of the grid blocks with the producer (1, 1, 1) and injector (25, 25, 1) wells are positioned at both corner ends of the reservoir. Each grid block has the dimension of (10 m X 10 m x 9 m).

Prior to the simulation study, the case model is being redesigned to suit the project objectives and to ease the evaluation of data. Further information on the grid size block and the reservoir parameters are as shown in Table 3. 2.

Table 3. 2: The parameters of the grid block and coal bed reservoir.

Grid system	25 x 25 x 1		
Well info	**Producing Well**	**Injection well**	
Well location	(1, 1, 1)	(25, 25, 1)	
Well radius	0.1197 ft	0.1197 ft	
Maximum Injection rate	-	2.12 x 10^5 scf/D	
Injection pressure and temperature	-	101.3 kPa at 15.7 ˚C	
Coal bed parameters			
Coal bed thickness	29.527 ft (9 m)		
Top of coal bed	3266.08 ft (995.5 m)		
Absolute permeability of natural fracture	4.00 mD		
Porosity of natural fracture	0.001		
Porosity of matrix	0.005		
Effective coal bed compressibility	1 x 10^{-6} /psia (1.45x10^{-7}/kPa)		
Initial reservoir conditions			
Initial reservoir pressure	1000 psi, 1350 psi and 1700 psi (Ranges from 6700 kPa to 12410 kPa)		
Initial reservoir temperature	25 ˚C, 30 ˚C, 35 ˚C, 40 ˚C, 45 ˚C and 51 ˚C		
Initial gas saturation	0.408		
Initial water saturation	0.592		
Water properties at reservoir initial condition			
Density	990 kg/m^3		
Viscosity	0.607 cp		
Compressibility	5.8x10^{-7}/kPa		
Langmuir Isotherm Parameters			
Parameters	**Methane. CH_4**	**Carbon dioxide, CO_2**	**Nitrogen, N_2**
Langmuir volume, G_L (m^3/kg)	Varied according to P&T condition as according to data from Appalachian basin (Seidle, 2011)		
Langmuir pressure, P_L (kPa)	4680	1903	2724

Modelled Langmuir pure component curves

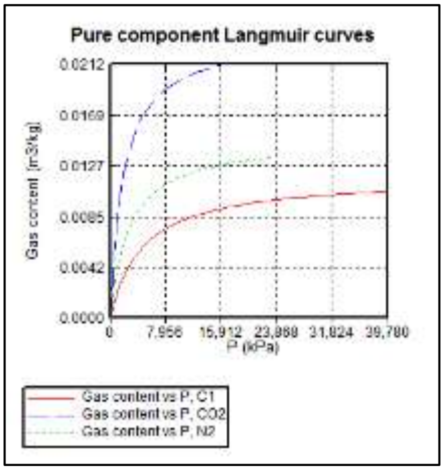

Figure 3. 7: The coal bed pure gas component Langmuir curves at 45 ˚C at 1350 psi as modelled by Law et al (2001).

Relative permeability data of the two (2) phase fluid

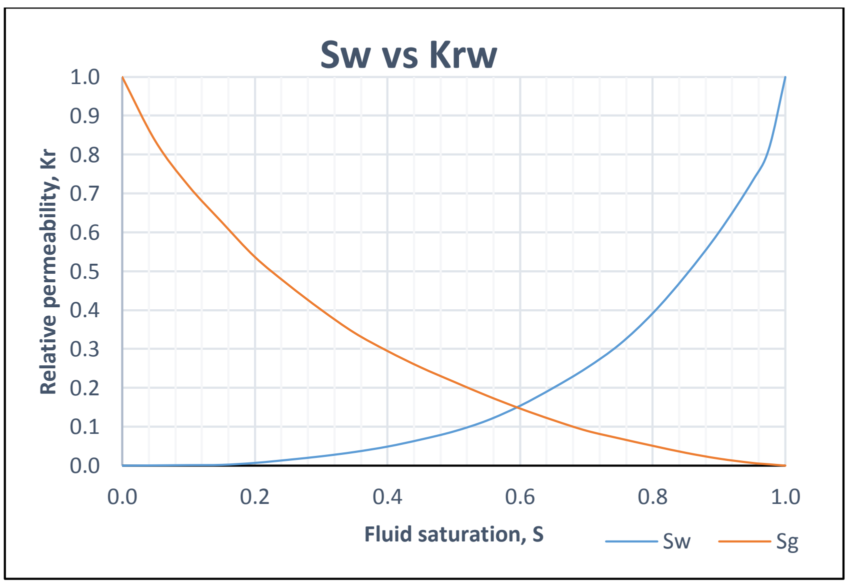

Figure 3. 8: The relative permeability graph for the two phase fluid from the initical case data of Law et al. (2001)

CHAPTER 4

RESULT AND DISCUSSION

The result and discussion chapter will discuss on the effect of reservoir temperature on the initially in place or adsorbed gas, methane (CH_4) and the injected gases (CO_2 and N_2) during enhanced coal bed methane (ECBM) recovery mode.

For the simulation study, the gas injection mode starts after 60 days of primary recovery. The simulation study is then run for 1460 days (4 years). After the simulation, the results are then compared for all cases and discussed in this chapter. As suggested by Saugier (2013) and Pashin and McIntyre (2003), the range of reservoir temperature for coal bed methane reservoir typically ranges from 27˚C to 51˚C and reservoir pressure of 1000 psi to 1700 psi.

4.1 The effect of reservoir temperature on CO_2-ECBM

The simulation study is done by varying the reservoir temperature at different initial reservoir pressure, while having CO_2-ECBM process to be running after 60 days of primary recovery. Below are the results of the simulation study.

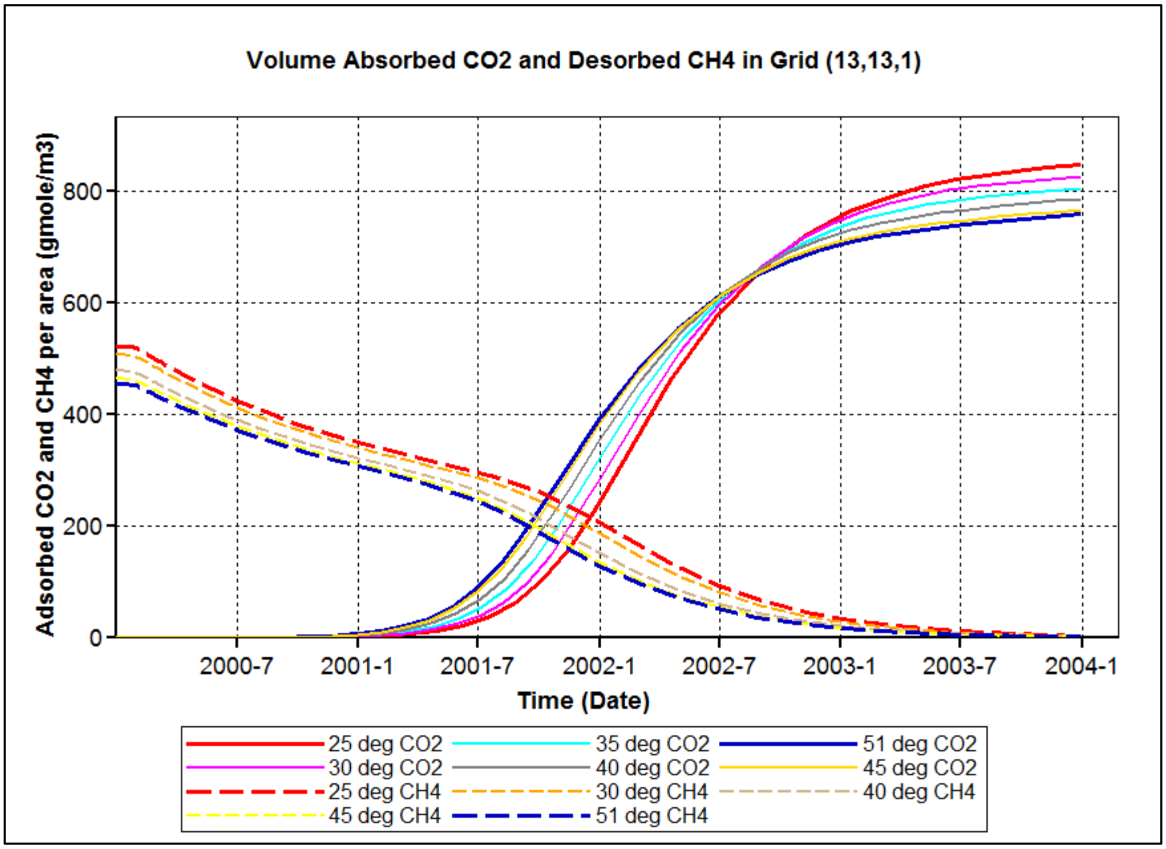

Figure 4. 1: The sorption of CO_2 and CH_4 at different reservoir temperature at initial reservoir pressure of 1350 psi.

Figure 4. 1 shows that the sorption process of the injected CO_2 gas and the initially adsorbed CH_4 gas. As shown in the graph, it takes time for the injected gas to reach the grid block (13,13,1).

Figure 4. 1 shows that the sorption capacity of coal is higher in lower reservoir temperature. The trend line of the initial in place CH_4 gas clearly shows that at 25℃, it is found that the volume of CH_4 gas initially adsorbed in place is higher than the one in higher reservoir temperature of 51℃.

Similar scenario is also seen in the trend line of the volume of adsorbed CO_2 as the gas is being injected to replace the initially in place CH_4 gas. As the volume of injected CO_2 gas reaches its plateau, the volume of adsorbed CO_2 is significantly higher at the lower reservoir temperature.

The findings on the decreasing adsorption capacity as temperature increases has been highlighted by Seidle (2011), Bae & Bhatia (2006), Sakurovs et al (2008) and Pini et al (2009) in their studies.

The decreasing adsorption capacity at higher reservoir temperature is contributed by some explainable reasons. Firstly, at higher temperature, the energy content of the gas is higher. Thus, the adsorbent or the coal bed requires more energy to retain the gas particles on its mono-layer surface. Plus, the high energy gas molecules tend not be adsorbed by the coal bed surface and freely let go to be available in the system.

Secondly, the high temperature alters the density of the adsorbate or the gas to be adsorbed. In general, the density of gas is decreasing as the temperature increases. The increase in temperature will induce lighter gas in which is difficult to be retained on the surface of coal via adsorption.

Thirdly, the saturated vapor pressure increases as the temperature increases, thus, causing difficulty in holding the adsorbate or gas molecules in its mono layer adsorption site. This theory is in agreement with the Clausius-Clapeyron relation which stated that the vapor pressure of any substance is increasing with the temperature in a linear trend.

The trend of the sorption behavior also occur at the different initial reservoir pressure. However, as predicted by Langmuir isotherm, the maximum adsorption volume of coal is higher at higher initial pressure.

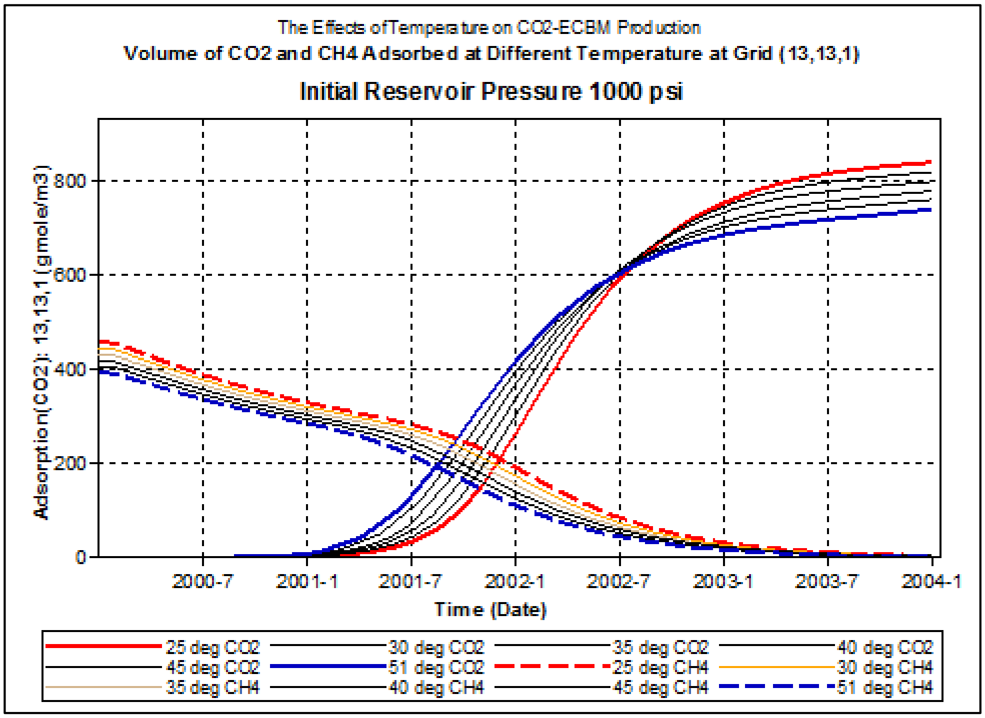

Figure 4. 2: The volume gas adsorbed at initial reservoir pressure of 1000 psi at different reservoir temperature, measured at grid (13,13,1)

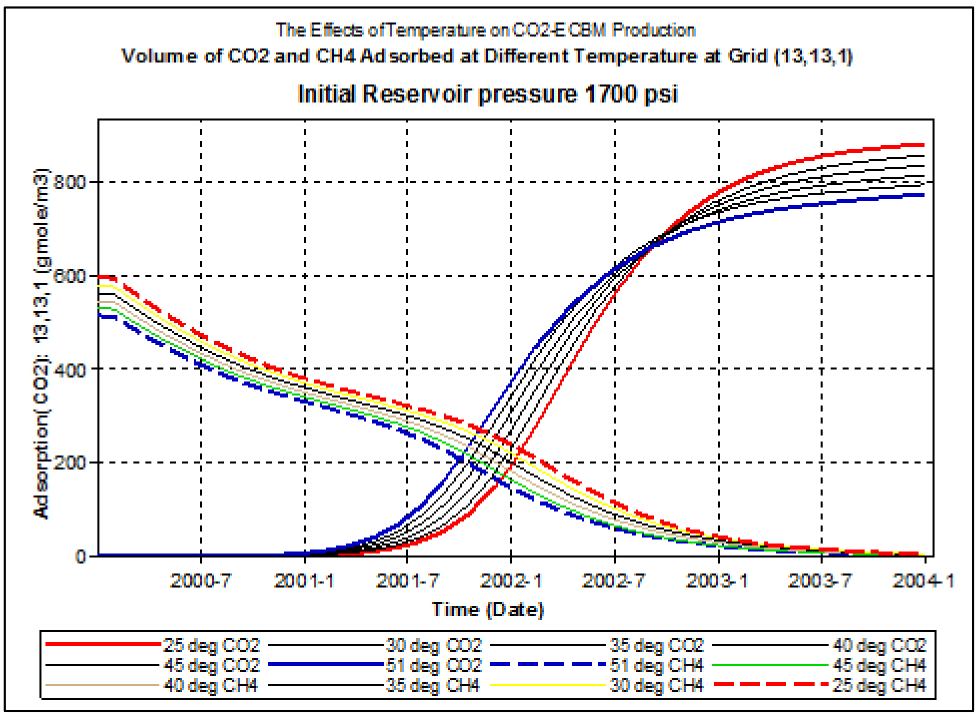

Figure 4. 3: The volume gas adsorbed at initial reservoir pressure of 1700 psi at different reservoir temperature, measured at grid (13,13,1)

Apart from the sorption capacity of coal to the gases, it is also found that in the early stage of CO_2-ECBM, the adsorption rate of CO_2 onto the coal bed is faster at higher reservoir temperature. The scenario is potrayed in Figure 4. 1, Figure 4. 2 and Figure 4. 3. The case is similar to the findings made by Busch et al (2004) and Zhang et al (2011).

At high reservoir temperature, the coal capacity to adsorb the injected CO_2 gas is lesser, thus allowing the injected CO_2 to propagate its sweeping flood front to be distributed at a higher rate. Due to the fast flood front at higher reservoir temperature, the injected gas of CO_2 takes lesser time to encroach into the producer well compared to the case in lower reservoir temperature. The comparison on the flood front is shown as per Figure 4. 4**.**

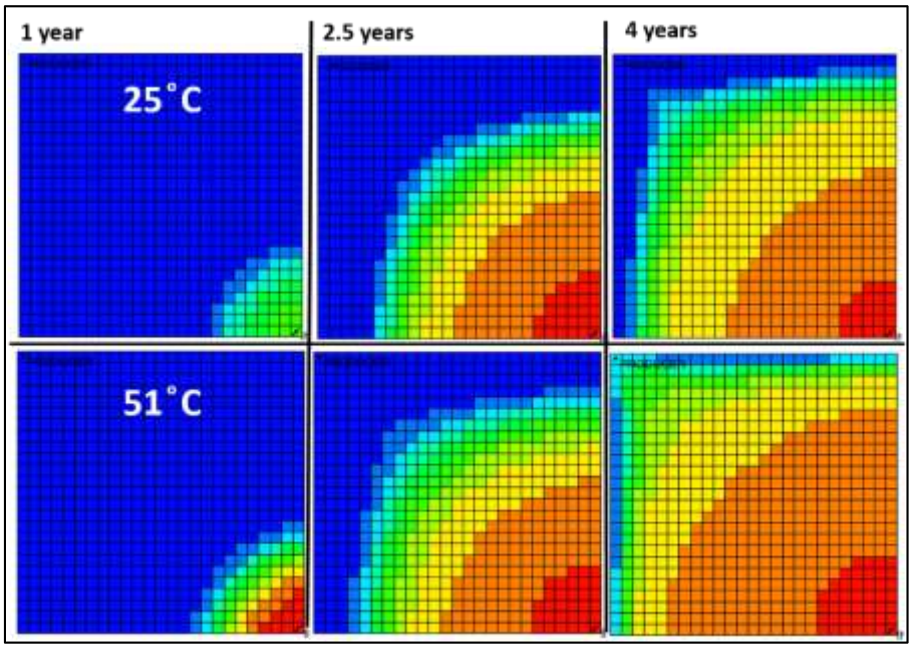

Figure 4. 4: The rapid sweeping flood front of injected CO2 gas at 51℃ and the slow sweeping flood front of injected CO2 gas at 25℃ at the time steps of 1 year, 2.5 years and 4 years.

From the figures above, it is evidenced that the rate of adsorption of CO_2 gas is more rapid at higher reservoir temperature as being stated by Busch et al (2004) and Zhang et al (2011). This finding is in accordance explained by Zhang et al (2011) which stated that at high reservoir temperature the injected gas molecules content higher energy that it can be readily be adsorbed onto the adsorption site.

Plus, the rapid sweeping flood front at higher reservoir temperature is also contributed by the lower adsorption capacity of the coal bed. The lower capacity of coal to retain the injected gas via adsorption allows the CO_2 gas to be sweeping faster from one grid block to another.

Apart from that, since it is known that the coal adsorption capacity decreases as reservoir temperature increases, lesser amount of CO_2 gas is needed to reach the equilibrium pressure at each grid block. Due to this, the faster flood front distribution is faster at higher reservoir temperature.

4.2 The effect of reservoir temperature on N_2-ECBM

The simulation work is then run in order study on the effect of reservoir temperature on the N_2-ECBM. The simulation result are as shown below:

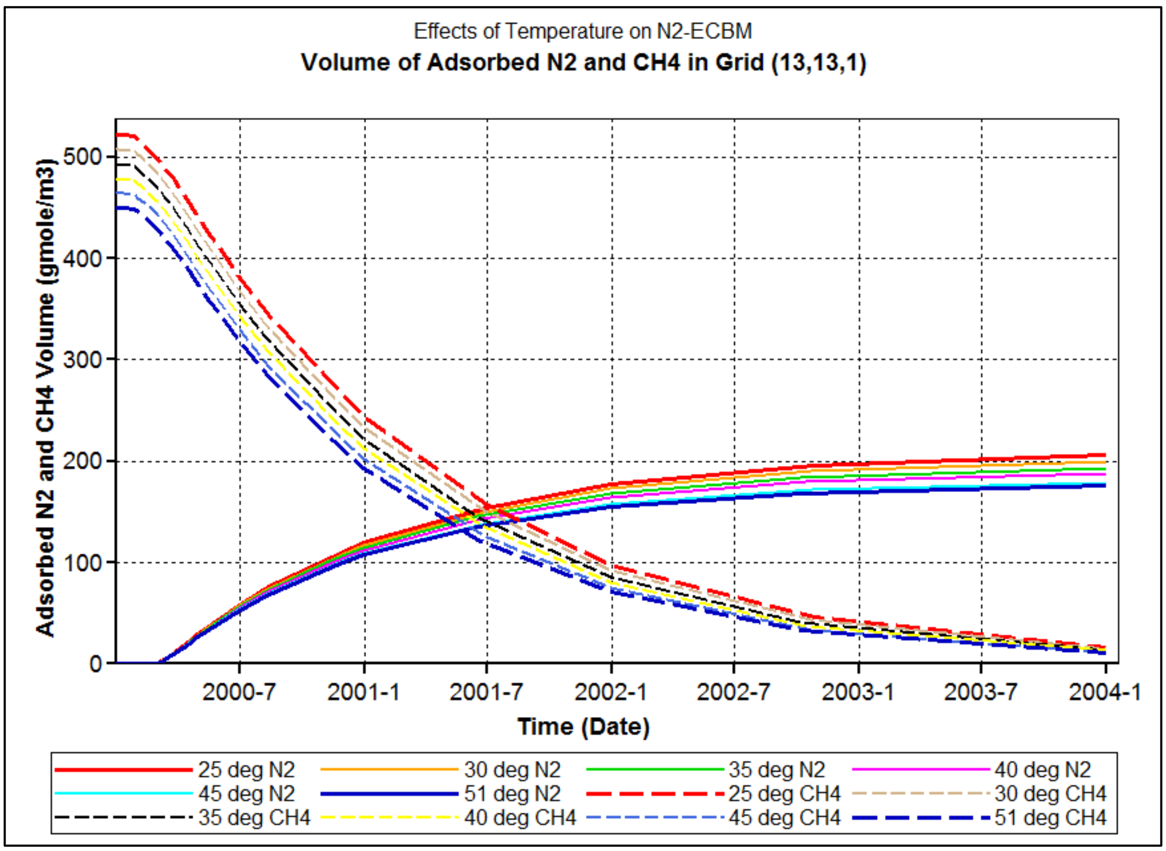

Figure 4. 5: The volume of N_2 and CH_4 sorption along with ECBM production duration at initial reservoir pressure of 1350 psi.

Similar to the simulation result on CO_2-ECBM, the coal has higher adsorption capacity at lower reservoir temperature. The trend line is however different from the trend line of the adsorption of CO_2 onto the coal bed body.

The trend line shows an increasing curve of adsorbed N_2 gas volume until it reaches plateau, which indicates the maximum capacity of coal adsorption capacity towards the injected gas as shown in Figure 4. 5.

However, the volume of adsorbed N_2 is significantly lower than the initially in place CH_4 during the ECBM phase. This phenomena is because the main mechanism of the ECBM with N_2 injection is by inert gas stripping or the partial pressure reduction mechanism as mentioned in the literature review chapter of the report. The injection of N_2 gas into the coal bed reservoir introduce an inert gas into the system in which increases in partial pressure as it is being injected into the reservoir along with time. As the partial pressure of the inert gas increases, the partial pressure of CH_4 is reduced, thus less preferred to be retained by adsorption by the coal bed and easily stripped off from the adsorbent.

Even though some volume of injected N_2 are being adsorbed by the coal bed, it is clearly shown that the maximum capacity of N_2 adsorbed is still lower than the original adsorbed CH_4 gas volume in place. As aforementioned in the literature review, it is known that coal has lower affinity to adsorb N_2 gas compared to the initially adsorbed CH_4. Due to this, even at the equilibrium point of the sorption, the maximum volume of adsorbed N_2 gas is lower than the initially adsorbed volume of CH_4 at all reservoir temperature cases. The explanation for this phenomena will be discussed in the next subchapter.

The trend of the decreasing volume of adsorbed gas especially N_2 is also occurred at the other lower initial reservoir pressure and higher initial reservoir pressure condition as shown in Figure 4. 5, Figure 4. 6 and Figure 4. 7. The figures below shows the similar trend of line.

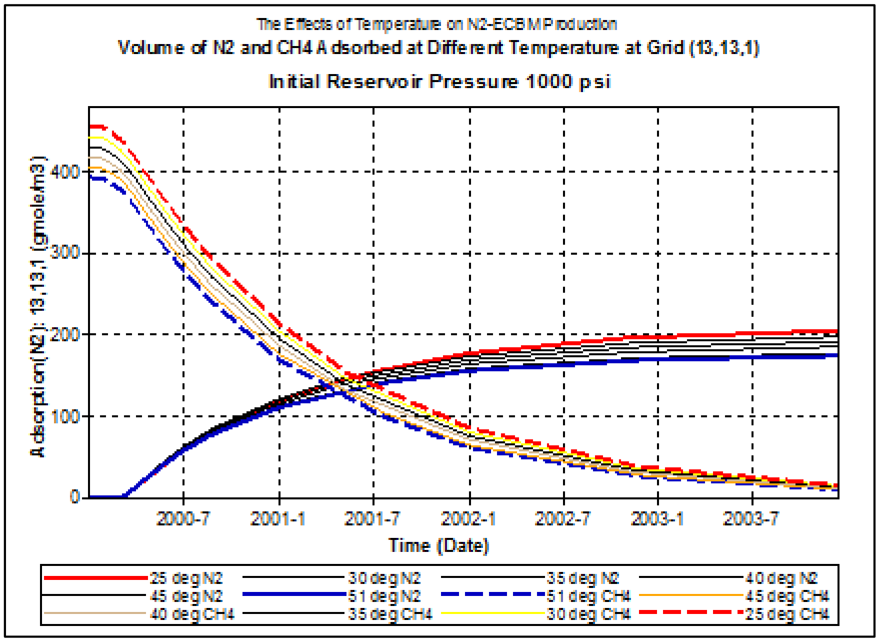

Figure 4. 6: The volume gas adsorbed at initial reservoir pressure of 1000 psi at different reservoir temperature, measured at grid (13,13,1)

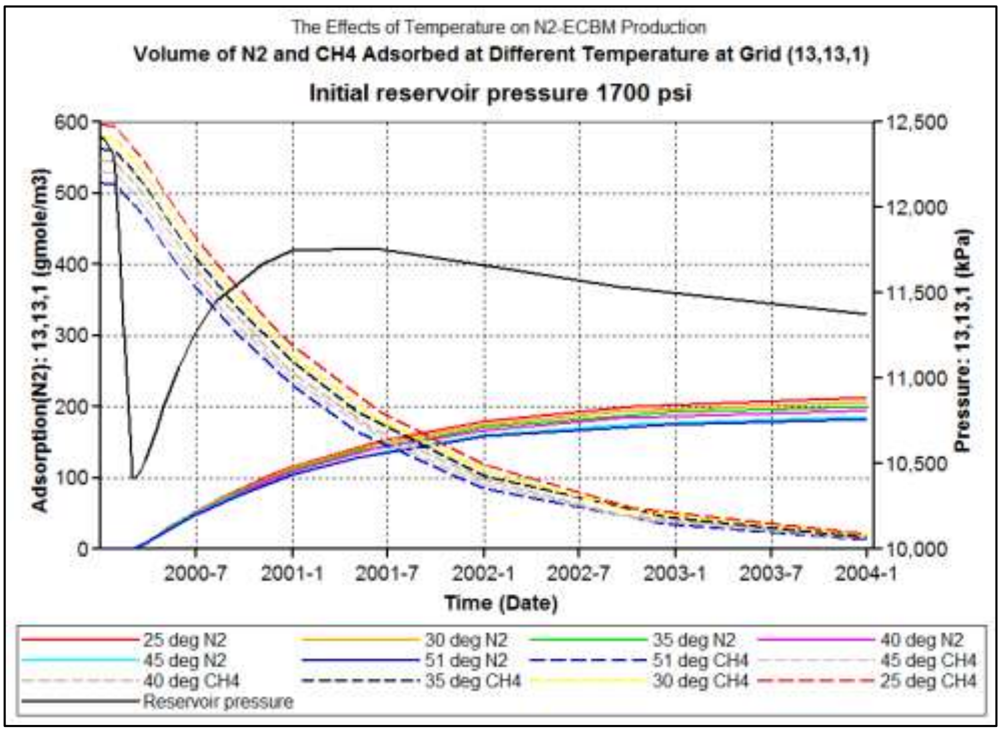

Figure 4. 7: The volume gas adsorbed at initial reservoir pressure of 1700 psi at different reservoir temperature, measured at grid (13,13,1). Observe the black line which represent the reservoir pressure. Initially it depleted at rapid rate during the primary recovery. After injection, the reservoir pressure increased due to the N_2 partial pressure increase.

In terms of sweeping flood front, there is not much different between the low reservoir temperature and high reservoir temperature condition in terms of the sweeping flood front shape. However, it is noticed that the sweeping flood front is more rapid at higher reservoir temperature. This is because of the low adsorption capacity of the coal towards N_2 at higher reservoir temperature, thus allowing lesser duration taken for the injected N_2 to be adsorbed to equilibrium or maximum adsorption capacity before moving to another grid block. The rapid sweeping flood front at higher reservoir temperature may causes early gas breakthrough in the N_2-ECBM due to the fast flooding from one grid block to another grid block.

The difference between the flood fronts at different reservoir temperature is shown in the Figure 4. 8 below.

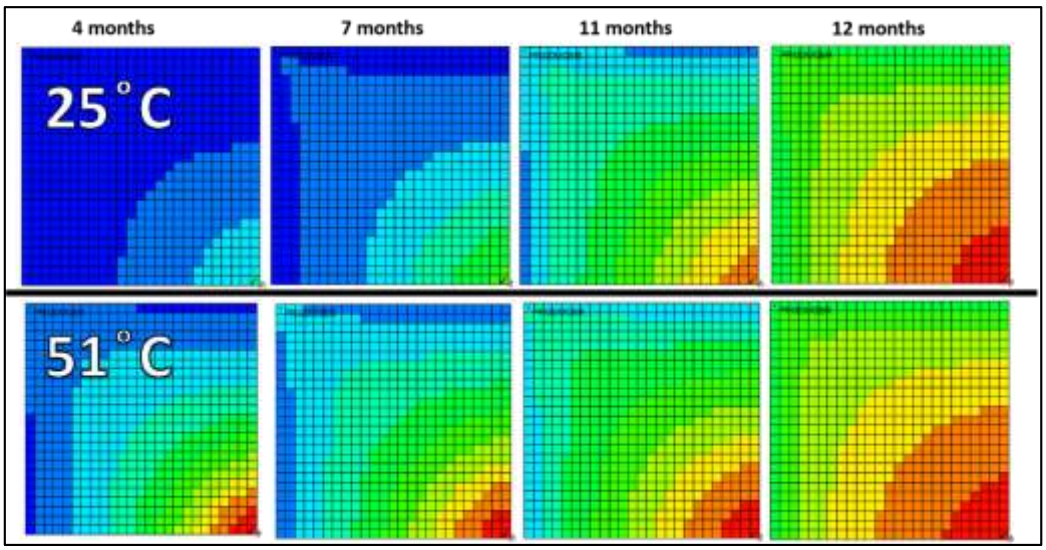

Figure 4. 8: The flood front for N2 injection at different reservoir temperature. The sweeping flood front is rapid at higher temperature and reaching gas breakthrough faster.

4.3 The comparison of N_2-ECBM and CO_2-ECBM at different reservoir temperature

Result from both simulation works are then compared in this subchapter. As being clearly shown in Figure 4. 1, Figure 4. 2, Figure 4. 3, Figure 4. 5, Figure 4. 6, and Figure 4. 7, it is clearly shown that the maximum volume of adsorbed CO_2 is almost doubled the volume of original CH_4 adsorbed in place, while, on the other hand, the maximum volume of N_2 gas adsorbed is approximately half of the original adsorbed CH_4 gas in place. The volume of adsorbed gases at different temperature is as per shown below in Figure 4. 9**:**

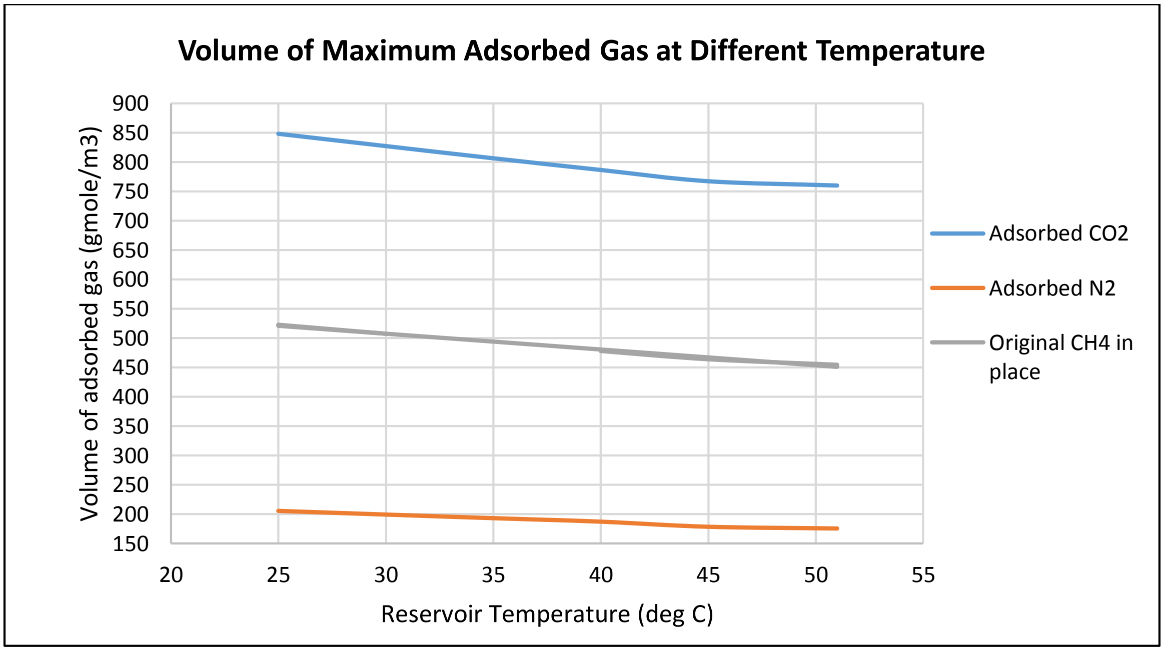

Figure 4. 9: The volume of maximum gases adsorbed at different reservoir temperature.

Due to this, it is deduced that the CO_2 is more prefered to be adsorbed by the coal bed body compared to N_2 gas at any reservoir temperature. This selective behaviour of coal adsorption towards carbon dioxide is commonly known as "carbon dioxide affinity to coal" (Florentin et al, 2009). The preferability of coal to adsorb CO_2 compared to N_2 and CH_4 is due to the difference in terms of gas molecular weight and gas thermodynamics.

Molecules with higher molecular weight has lower rate of vaporization, thus, lower rate of desorption. According to this theory, CO_2 gas, which has heaviest molecular weight of 44.01 g/mol compared to the CH_4 (16.04 g/mol) and N_2 (14.01 g/mol), has lower evaporation rate. This ensure that the CO_2 gas can be easily be adsorbed and retained onto the coal bed body compared to those two (2) gases.

Apart from difference in terms of the coal sorption capacity towards these gases, it is also importance to analyze on the flood front of the injected gas. The flood front is part of the crucial design of the effective ECBM program. From the result shown in Figure 4. 4 and Figure 4. 8**,** it is known that the most effective ECBM program would be by having CO_2 injection in low temperature reservoir.

This is because the flood front will sweep slowly in a disperse manner and saturated distributed among the grid blocks compared to the rapid, fast flood front N_2 injection at high reservoir temperature. By having slow and steady flood front, more effective sweeping mechanism can be achieved and early gas breakthrough can also be avoided. By injecting CO_2 during ECBM, an efficient volumetric displacement and a delayed gas breakthrough program can be established.

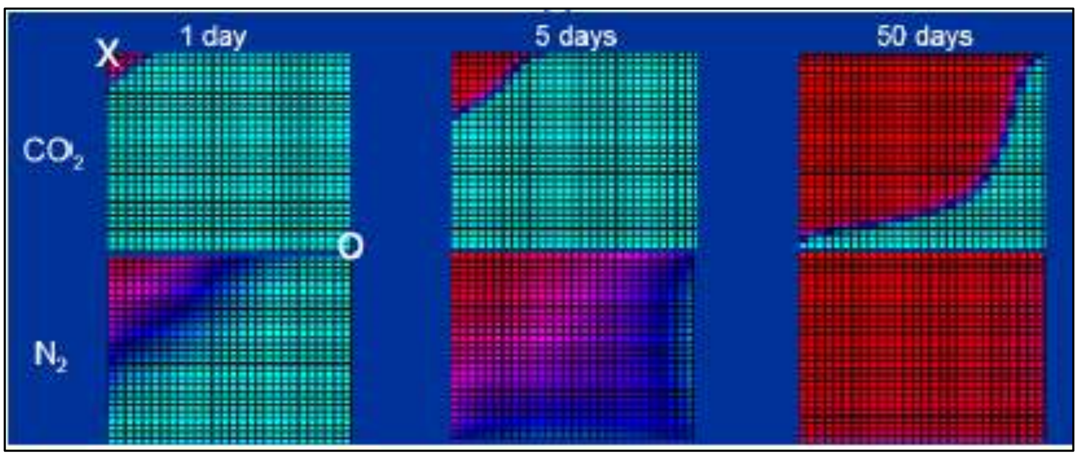

Figure 4. 10: The difference between "shock" CO_2 flood front and "disperse" N_2 flood front (Oudinot et al, 2007)

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

It is concluded that from result of the simulation work that reservoir temperature does influence the sorption behavior of the injected gas into the coal bed methane reservoir. It is stated that the coal adsorption capacity towards gases decreases as reservoir temperature increases. A more profitable ECBM project is attained by injecting CO_2 into coal bed reservoir of lower reservoir temperature since the flood front will be slower and steadily progress from one grid block to another grid block. In this case, the injected CO_2 gas will be saturated and adsorbed before moving on to the next grid blocks. It is also known that the adsorption process takes lesser time to reach equilibrium at higher temperature.

In conclusion, the project benefits on the understanding towards the sorption behavior of CO_2 and CH_4 based on the effects of temperatures.

In the future, it is important to consider on the gas type and gas injection rate in designing an effective ECBM and to prevent early gas breakthrough. Engineers should also be attentive in designing their ECBM program since simple physical properties of nature such as the pressure and temperature will influence on the sorption behaviors of CBM reservoir.

As for the future recommendations, few more aspects of coal bed methane study should be focused in the future to provide more understanding towards the CBM reservoir system. The suggested topics are as follows:

- The laboratory works on the effects of reservoir temperature on CO_2 and N_2 gas injection during ECBM to observe the sorption behavior in microscopic scale.
- The swelling behavior of CO_2 adsorption.

- The effect of injection temperature and pressure in ECBM production
- Mathematical modelling for simultaneous fluid flow and gas-flow dynamics in coal bed reservoir.
- Design techniques to optimize CO_2 sequestration and methane production in coal beds.

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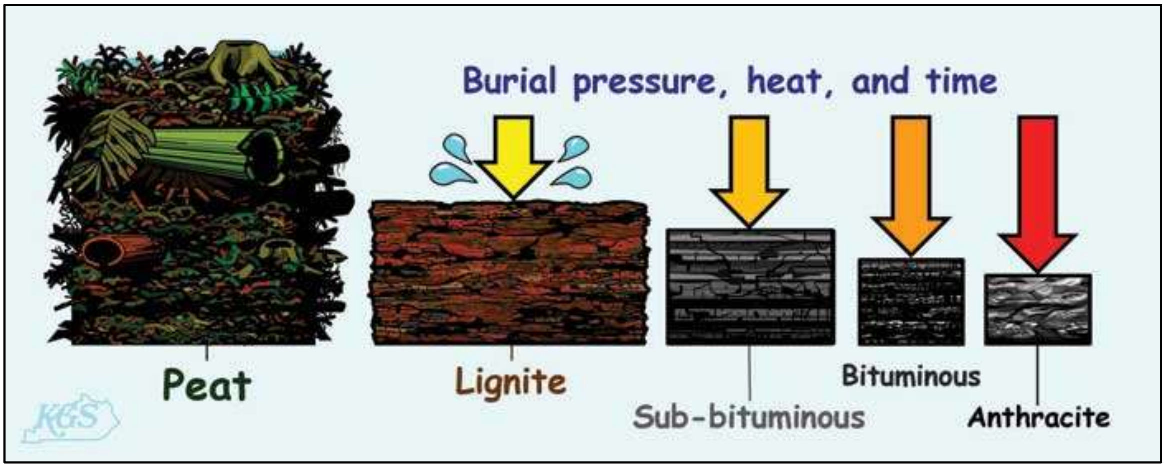
APPENDICES

Appendix 1: The increasing coal ranks arranged from left to right. (Source: Stovesonline.co, 2014)



Appendix II: The phases of coal bed methane production (Aminian, 2006 & 2007).