SECONDARY RECOVERY FOR THE OPTIMIZATION OF COAL BED METHANE (CBM) PRODUCTION. A SIMULATION STUDY

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CERTIFICATION OF APPROVAL

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Approved by,

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(Ms. Siti Sarah Salehudin)

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MAY 2013

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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HAYATUL NADIA BINTI ANNUAR

ABSTRACT

The CBM industry is exploring new methods of enhancing the gas production. This is done by experimenting with the injection of nitrogen (N_2) and carbon dioxide (CO_2) into the coal bed in order to displace methane along the coal face cleats. The gas exchange results in incremental methane production rates as compared to just decreasing the hydrostatic pressure like the primary recovery process.

Coal can replace 25% to 50% of methane gas storage capacity with nitrogen and studies indicate that for each volume of nitrogen injected will result in two volumes of methane produced. While for carbon dioxide, laboratory studies shows that coal can adsorbs nearly twice volume of CO_2 than methane. However, different rank of coal will have different acceptance towards gas injected as pressure dependent parameters also vary relative to the rank. Therefore, this paper will studied on the effect of different composition of both gases that can enhance the CBM recovery for different rank of coal.

The first part of the research shows that for all injection composition, medium rank gives the highest methane production which proves that medium rank coal is the best coal rank for CBM process. As the research goes by it shows that as coal rank increases, more nitrogen or low carbon dioxide is needed to enhance the CBM recovery which this is due to the pressure dependent parameter varies between coal ranks.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1.1 Background

Methane (CH_4) is the primary energy source of natural gas. Coal Bed Methane (CBM) is simply methane found in coal seams. The gas storage mechanism is unlike with conventional reservoir. In typical gas reservoir, gas is compressed by the pressure of the formation while in a coal reservoir the gas is stored within the coal matrix by a process known as adsorption. Adsorption means accumulation of molecules of a gas to form a thin film on the surface of a solid. In Coal Bed Methane, adsorption taking place by the gas molecules adhere to the surface of the coal. (Fekete Association Inc., 2011). Besides than adsorption process, CBM is also stored as absorption gas, free gas and dissolved gas in water within the coal.

CBM is sweet gas as it does not contain hydrogen sulfide. The methane gas in CBM is in a near-liquid state lining inside of pores within the coal which is called the matrix. The open fractures in the coal which is the cleats can also contain free gas or can be saturated with water. Unlike conventional gas reservoirs, coal is both the reservoir rock and the source rock for methane. Coal is heterogeneous and anisotropic porous media which is characterized dual porosity systems which is macropores and micropores. (Aminian, 2003). The macropores, also known as cleats, constitute the natural fractures common to all coal seams. There are two types of cleat which are face cleats and butt cleats. Face cleats act as the main channel for flow in CBM while butt cleat typically terminate perpendicular to a face cleat. While for micropores or the matrix, it contains the vast majority of the gas.

Unlike much natural gas from conventional reservoir, coal bed methane contains very little heavier hydrocarbons. It often contains up to a few percent of carbon dioxide.

Some coal seams, such as those in certain areas of the Illwara Coal Measures in NSW, Australia contain little methane with the predominant coal seam gas being carbon dioxide.

There are two processes for the formation CBM:

1) Biogenic: Biogenic methane is produced by anaerobic bacteria in the early stage of coalification
2) Thermogenic: Thermogenic methane is mainly during coalification at temperatures of 120-150^{o}C

1.2 Problem statement

Carbon dioxide has a greater adsorption capacity than methane on coal which is up to ten times depending on coal rank. However, as CO_2 molecule is larger than methane molecule, when CO_2 replaces methane onto the coal surface it tends to swell the coal thus closing the cleats. Consequently, permeability decreases. Thus, the production decreases. While nitrogen (N_2) has a lower adsorption capacity than methane but N_2 molecule is smaller than the methane molecule. As N_2 replaces methane in the reservoir, coal shrinkage thus enhancing the matrix shrinkage processes and increase the permeability. When the permeability of the reservoir increase the production will also increases. The N_2 threshold also varies between coal ranks, as pressure dependent parameters also vary relative to coal rank. Therefore, injection gas with a mixture of CO_2 and N_2 is proposed in order to study the effect of different composition to different coal rank to the CBM recovery.

1.3 Objectives

The objectives of this research are:

1) To simulate the effect of different composition of Carbon Dioxide (CO_2) and Nitrogen (N_2) gas injections on different rank of coal to the methane production.
2) To identify the optimum composition of injection for specific coal rank

1.4 Scope of study

The project will cover on:

- The coal rank will be divided to three which is low rank coal, medium rank coal and high rank coal due to lack of data. Therefore some of the values for input parameters are in ranges of the specific coal rank.
- Different composition of gas injection used will be 30 CO_2/ 70 N_2, 50 CO_2/ 50 N_2 and 70 CO_2/ 30 N_2

CHAPTER 2

LITERATURE REVIEW

2.1 Properties of Coal Bed Methane

Gas contained in CBM is mainly methane and trace quantities of ethane, nitrogen, carbon dioxide and few other gases. The porosity of CBM is usually very small which is in the range of 0.1 - 10%. The adsorption capacity of coal is defined as the volume of gas adsorbed per unit mass and it is expressed in unit of SCF (standard cubic feet) gas/ton at standard pressure and temperature condition. The capacity to adsorb is also depends on the rank and quality of the coal. Sub-bituminous coal is believed to be the best coal for CBM. It is a type of coal which has properties ranging from those of lignite to those of bituminous coal.

For most coal seams found in US the adsorption range is usually between 100 to 800SCF/ton. While for the permeability of CBM, the higher the permeability, the higher the gas production. The permeability of coal seams is usually lies in the range of 0.1 to 50 milliDarcies for most coal seams found in the US.

2.2 Principal of adsorption

Most of the gas in coals is stored by adsorption in the coal matrix. Therefore pressure-volume relationship is defined by the adsorption isotherm and not by real gas law. (Aminian, 2003). In 1938, Brunauer categorized the adsorption of gas on a solid into five types of isotherms. “Isotherm” refers to the volume of gas adsorbed on a solid surface as a function of pressure for a specific temperature, gas and solid material.

According to Brunauer's classification, a Type I isotherm, as characterized by figure 1 applies the adsorption of gases in microporous solids (the matrix). At high pressure, the amount of adsorbed increases but at higher temperatures, the amount adsorbed decreases. Type I isotherm closely describe the adsorption behavior of methane on coals, and the model has been applicable without exception. The Langmuir equation fits the adsorption data of methane on coal and is used exclusively in the CBM process. (Rogers, 2007)

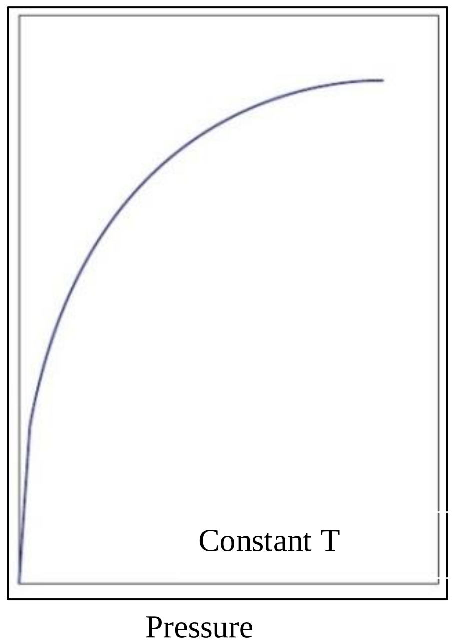


Figure 1: Type 1 isotherm of Brunauer, Emmer and Teller (BET)

As pressure in coal seams increases with depth or with the hydrostatic head of water, the capacity of the coal for adsorbing more methane improves. Adsorption capacity of coal is defined as the volume of gas adsorbed per unit mas of coal which usually expressed in SCF (standard cubic feet) gas/ton of coal.

2.3 Coal Rank

Coal is classified into four general categories or ranks. They are range from lignite through sub-bituminous and bituminous to anthracite. They start off as peat. Due to amount of time, heat and burial pressure, it is then metamorphosed to lignite. Lignite is considered as immature coal because it is light in colour and it is remain soft. As time passes, lignite increase in the maturity and change to sub-bituminous coal where it become darker and harder. As this burial and alteration process continues, more chemical and physical changes occur and coal is then classified as bituminous. Bituminous coal is dark and hard. Anthracite is the last of the classifications, very hard and shiny and this terminology used when then coal has reached ultimate maturation.

The degree of alteration or metamorphism that increases the maturity of the coal is referred to as the rank on the coal. Low rank coals include lignite and sub-bituminous coals where they have lower energy content due to low carbon content. They are lighter and have higher moisture levels. As time, heat and burial pressure increases the rank of the coal will also increase. While for high rank coals, it is include bituminous and anthracite coals which contain more carbon and much higher energy content than the low rank coal. In addition, high rank coals have more shiny appearance and lower moisture content. (Kentucky geological survey, 2012)

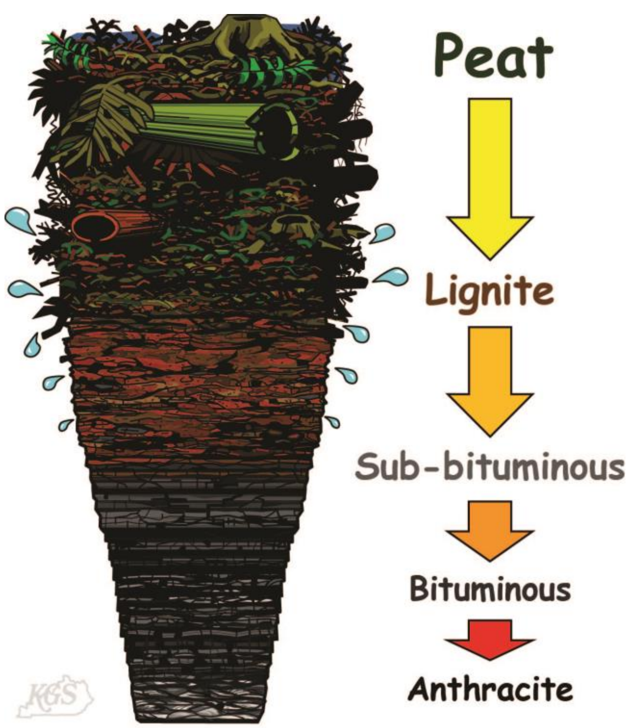


Figure 2: Coal rank. Source: **(Greb, 2012)**

2.4 Langmuir Isotherm

Adsorption Isotherm is defined as amount of gas that is adsorbed on solid surface as a function of pressure at constant temperature. There are several sorption Isotherm theories have been developed but Langmuir's theory is the frequently used for CBM. (Firanda, 2012). The assumptions for this theory are:

1. One gas molecule is adsorbed at a single adsorption site
2. An adsorbed molecules does not affect the molecule on the neighboring site
3. Sites are indistinguishable by the gas molecules.
4. Adsorption is on an open surface and there is no resistance to gas access to adsorption sites.

The Langmuir equation is expressed as:

$$V = V_L \frac{P}{(P_L + P)} \tag{1.1}$$

Where,

V = Volume of gas adsorbed (SCF/ton)

P = Pressure (psia)

VL = Langmuir volume constant (SCF/ton)

PL = Langmuir pressure constant (psia)

The above equation assumes pure coal and for application in the field. The equation is modified to account for ash and moisture contents of the coal:

$$V = (1 - f_a - f_m) \frac{V_L P}{P_L + P} \tag{1.2}$$

Where: fa = Ash content, fraction

fm = Moisture content, fraction

2.5 Methane production

Primary production initially goes through a process called dewatering where only water is produced from the cleat system at the beginning. The dewatering process takes place by reducing the reservoir pressure. Thus result in reduction in the partial pressure of gas from the matrix and the coal. Desorption of methane begins as the reservoir reaches a critical pressure. As pressure decreases, the methane gas will desorb from the coal surface and flow through fractures toward the well bore. (Agrawal, 2007).

Water rate will decreases and the gas rate increases until the gas peak is reached. Finally when the depletion in the reservoir is significant, the gas rate will decline. This is because as reservoir pressure is reduced during production, porosity and permeability in the system are also reduced (Mora, 2007). Table 3 below shows the typical production profile for a CBM well.

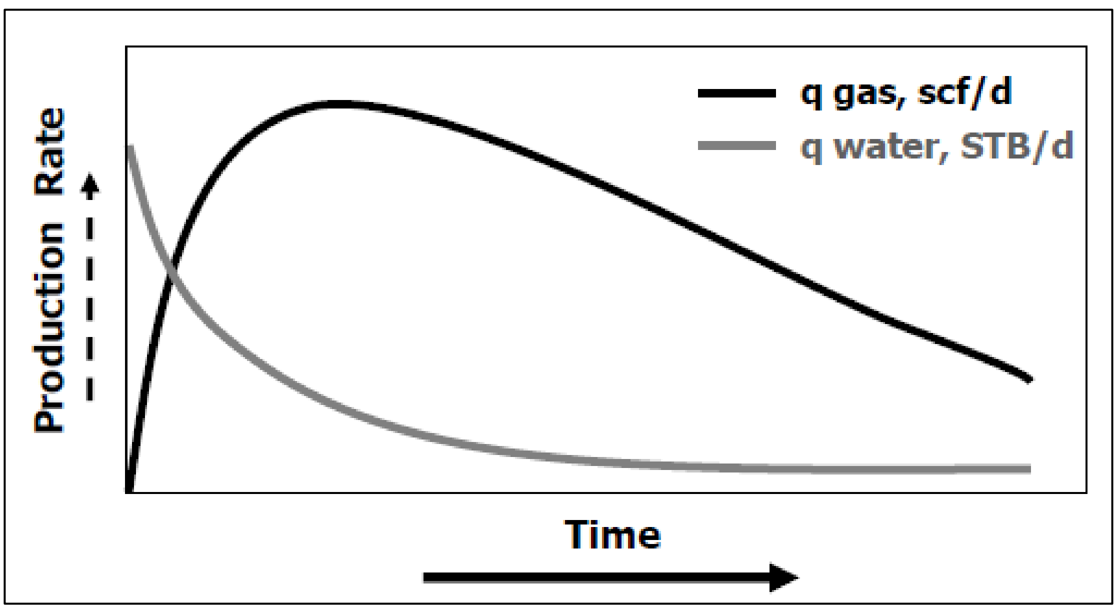


Figure 3: Typical Production Profile for a CBM well. Source: (Mora, 2007)

CHAPTER 3

METHODOLOGY

3.1 Research Methodology & Project Activities

The methodology for this project is illustrated as below:

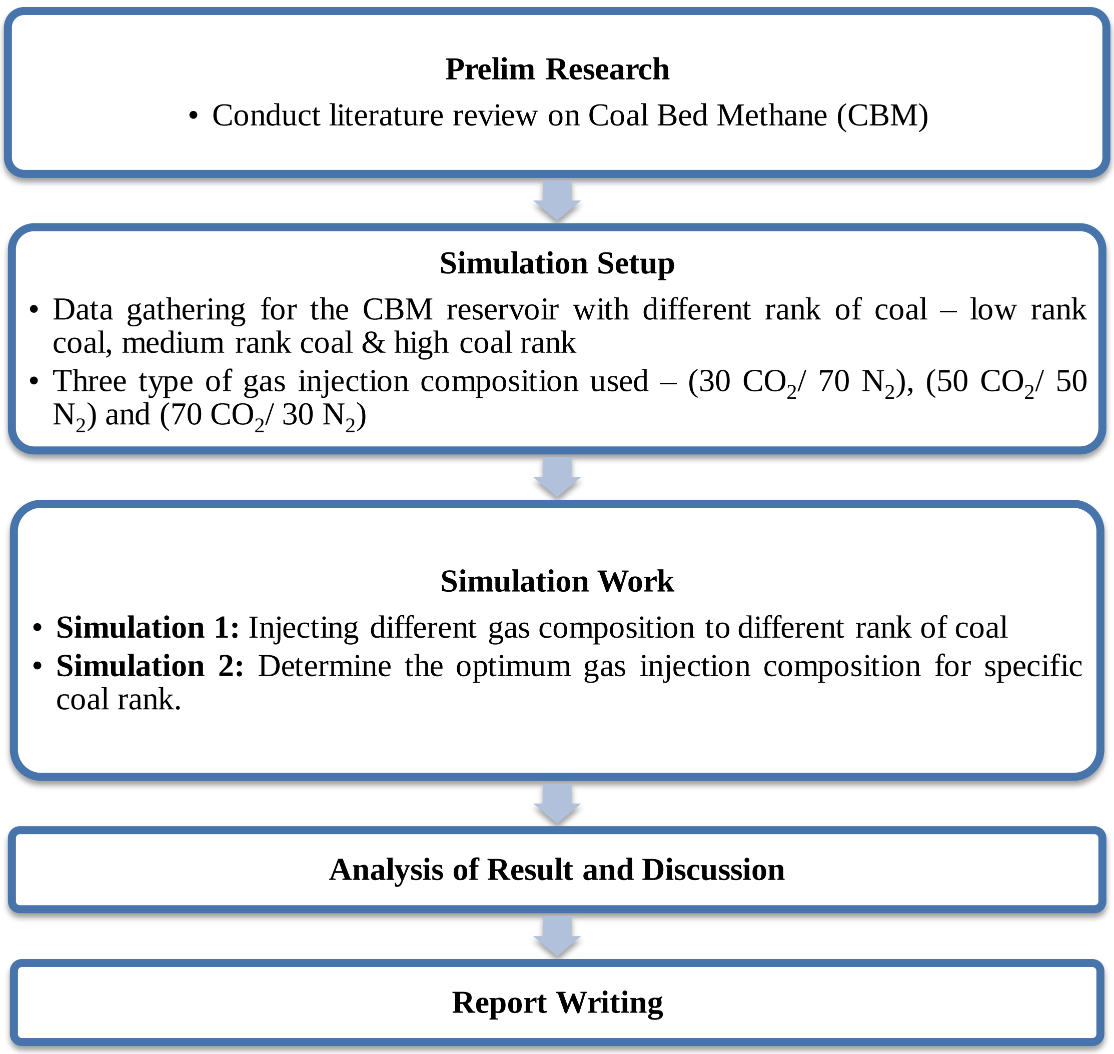


Figure 4: the research methodology and project activities

3.2 Key Milestone

The project key milestone is divided into three stages combining FYP 1 and FYP 2 activities. First stage is the familiarization with the project and research works on the project title and second stage is for the data gathering and developing the results. The third stage is the final stage where student needs to submit full project report at the end of the semester.

Table 1: The project key milestone

Details	Week
First stage • Selection of project topic • Preliminary Research Work • Submission of Extended Proposal • Proposal Defence	1-9
Second stage • Project work continues • Submission of Interim Report • Submission of Progress Report	10- 23
Third stage • Pre-SEDEX • Submission of draft report • Submission of Dissertation • Submission of Technical Paper • Oral Presentation • Submission of the project report	24-28

3.3 Gantt Chart

No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project work continues								Mid semester break								
2	Submission of Progress Report																
3	Project work continues																
4	Pre-SEDEX																
5	Submission of Draft Report																
6	Submission of Dissertation (soft bound) & Technical Paper																
7	Oral presentation																
8	Submission of Project Dissertation (Hard Bound)																

Process

3.4 Tools Required

Software used for the project is:

1. Eclipse 300 for Coal Bed Methane (ECBM)

3.5 Model construction

Three gas injection compositions will be used for this project where one with equal composition of CO_2 and N_2, one with high composition of CO_2 and one with higher composition of N_2 in order to know the effect of having higher composition of CO_2 or N_2. The gas injection compositions are as below:

I. 30% CO_2/ 70% N_2
II. 50% CO_2/ 50% N_2
III. 70% CO_2/ 30% N_2

Besides, coal ranks used for this project are classified to three types which are:

I. Low rank coal
II. Medium rank coal
III. High rank coal.

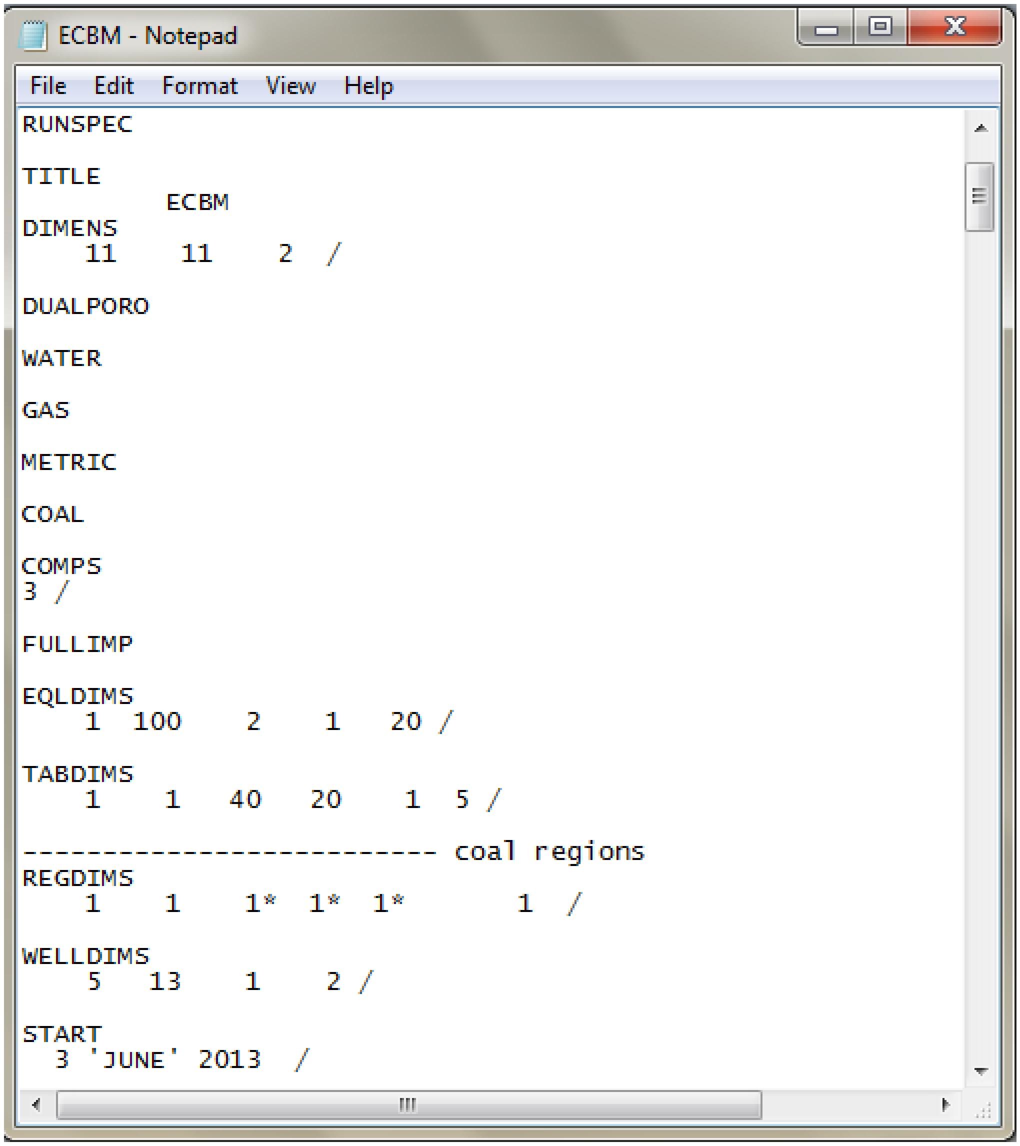
Low rank coal is lignite since it has low carbon content (10-20%). Medium rank coals are bituminous and sub-bituminous because of medium content of carbon in it (35-80%) and high rank coal is defined for anthracite since it has high carbon content (80-96%).

In order to obtain more accurate result, some input parameter are put to be fixed. All fixed input parameter are attached at the appendix. While some of the input parameters are varied as different coal rank has different properties. Below is the varied input parameters for all coal ranks. Some of the input parameter are in average ranges of specific coal rank. Time for the production were fixed to 150 days for all cases.

Table 2: Varied input parameters per coal rank

Parameter	Low rank	Medium rank	High rank	Unit
Density	753	793	864.5	kg/m^3
Permeability	100	25	1	mD
Porosity	0.015	0.005	0.0025	-
PL CO_2	27.579	17.237	13.789	Bar
VL CO_2	0.032574884	0.041239447	0.05670424	sm^3/kg
PL N_2	124.11	96.527	68.948	Bar
VL N_2	0.00723884	0.013746482	0.018901413	sm^3/kg
PL CH_4	51.711	34.474	17.926	Bar
VL CH_4	0.01085829	0.027492965	0.03780283	sm^3/kg
Rock compressibility, Cp	7.25E-03	5.00E-03	2.90E-03	1/bar
Matrix compressibility, Cm	1.50E-05	1.00E-06	7.30E-05	1/bar
Carbon content	0.15	0.575	0.88	%

The ranges of the input parameters are as tabulated in the appendix. While Figure 4 shows the keyword used for the simulation. Eclipse 300 is used as it is for compositional model. For this simulation three compositions are used which are methane (CH_4), carbon dioxide (CO_2) and nitrogen (N_2).



```
RUNSPEC

TITLE
         ECBM
DIMENS
    11     11     2  /

DUALPORO

WATER

GAS

METRIC

COAL

COMPS
3 /

FULLIMP

EQLDIMS
    1  100     2     1    20 /

TABDIMS
    1     1    40    20     1   5 /

-------------------------- coal regions
REGDIMS
    1     1     1*   1*   1*        1   /

WELLDIMS
    5    13     1     2 /

START
  3 'JUNE' 2013   /
```

Figure 5: Keyword data used for the simulation

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Effect of different injection composition on different rank of coal to the methane production

The objective of the study was to simulate the effect of different composition for different rank of coal to the methane production. Therefore three type of composition of gas injection will be injected to every coal rank. The following section presents the finding for specific gas injection composition.

4.1.1 Injection composition of 30 CO_2 / 70 N_2

Below is the result of total methane production by injecting composition of 30 CO_2 / 70 N_2 of gas to every coal rank.

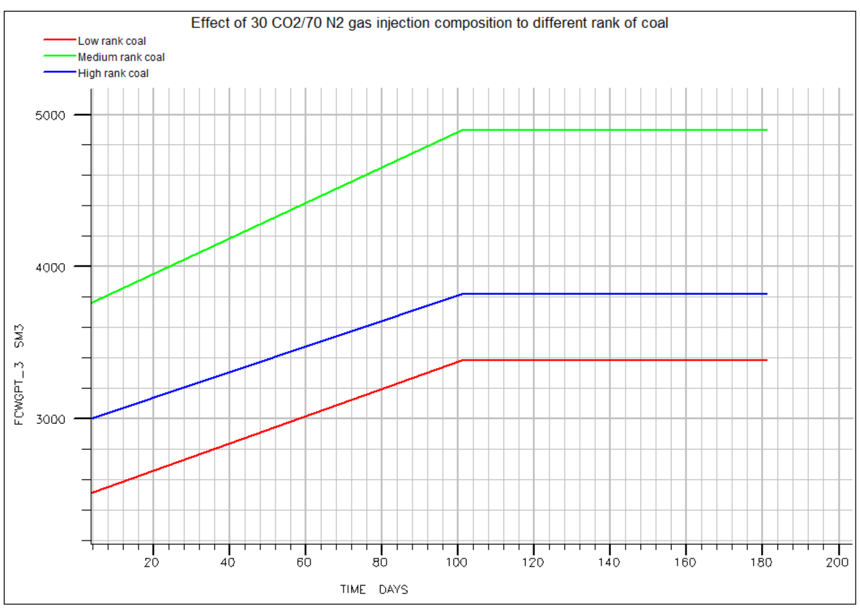


Figure 6: Total production of methane using composition of 30 CO_2 / 70 N_2 to every coal rank.

Based on the graph above, by injecting composition of 30 CO_2 / 70 N_2 gas results in medium rank coal produce the highest methane followed by low rank coal and lastly high rank coal. Medium rank coal also shows faster production than other rank of coal. While for high rank coal, it produces faster than low rank coal until day 50 but end up to produce lower than low rank coal at the day of 101th. Table 3 shows the methane production for all coal ranks.

Table 3: Total production of methane using composition of 30 CO_2 / 70 N_2

Coal rank	Low rank coal	Medium rank coal	High rank coal
Total production of methane (sm^3)	3380	4896	3814

4.1.2 Injection composition of 50 CO_2 / 50 N_2

The result of total methane production by injecting composition of 50 CO_2 / 50 N_2 gas injections to coal ranks.

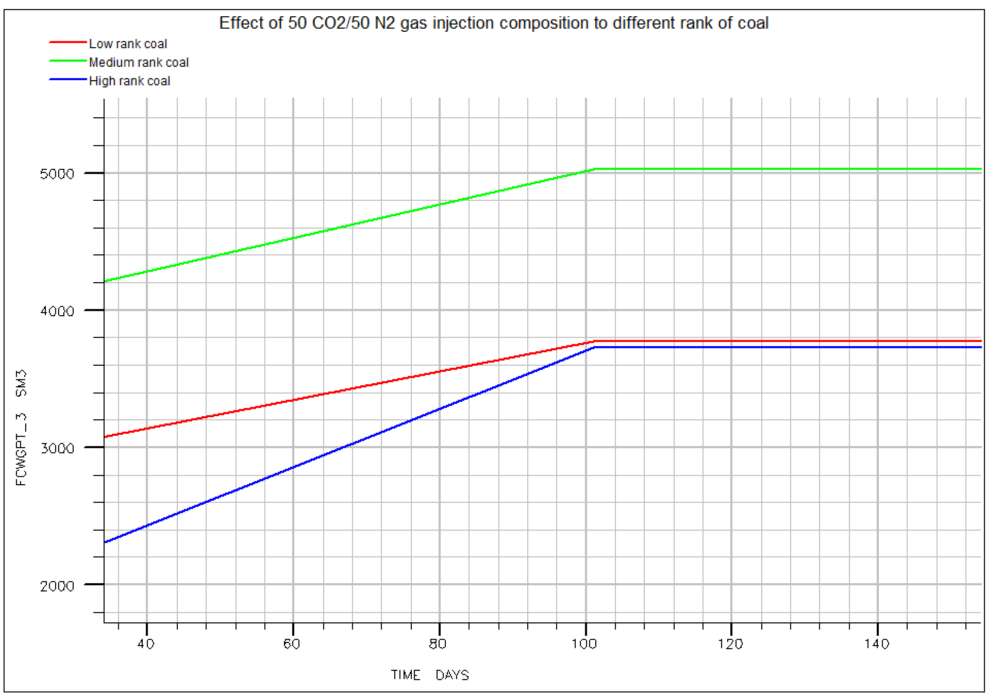


Figure 7: Total production of methane using composition of 50 CO_2 / 50 N_2 to every coal rank.

Injection composition of 50 CO_2 / 50 N_2 also results in medium rank coal having the highest methane production followed by low rank coal and high rank coal. Medium rank coal also show to have faster production. However compared to previous injection composition, high rank coal start produces slower than low rank coal and end up to have the less methane production. Table below shows the methane production for all coal rank and the production shows to be different from the previous injection composition.

Table 4: Total production of methane using composition of 50 CO_2 / 50 N_2

Coal rank	Low rank coal	Medium rank coal	High rank coal
Total production of methane (sm^3)	3771	5027	3726

4.1.3 Injection composition of 70 CO_2 / 30 N_2

Total methane production by injecting 70 CO_2 / 30 N_2 to every coal ranks are as below.

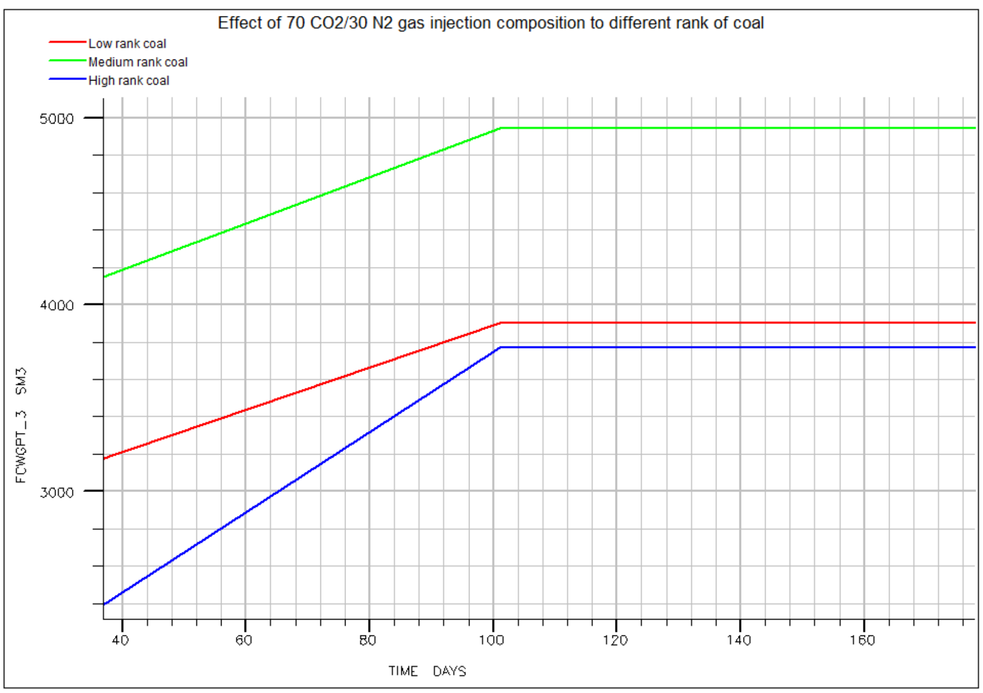


Figure 8: Total production of methane using composition of 70 CO_2 / 30 N_2 to every coal rank.

Injection composition of 70 CO_2 / 30 N_2 gives the same result as injection composition of 50 CO_2 / 50 N_2 where the highest methane production is by medium rank coal followed by low rank coal and high rank coal. Table 5 summarizes the methane production for all coal rank and the methane production of specific coal rank is different from the previous two gas injection composition.

Table 5: Total production of methane using composition of 70 CO_2 / 30 N_2

Coal rank	Low rank coal	Medium rank coal	High rank coal
Total production of methane (sm^3)	3901	4940	3771

4.1.4 Discussion for the effect of injection composition to different rank of coal

Results shows that for all injection composition, medium rank coal gives the highest production followed by low rank coal and lastly high rank coal but with different methane production for specific coal rank.

The reasons of medium rank coal having the highest production is because it has the average of porosity, permeability and carbon content. Low rank coal may have the highest porosity and permeability but it has the lowest carbon content while high rank coal has the highest carbon content but it has the lowest porosity and permeability. Thus, the results proves that medium rank coals are the best coal rank for CBM production.

In addition, different composition of gas injection affect the methane production is due to the pressure dependent parameter as it varies relative to the rank. Different coal ranks have different differential swelling for $C0_2$ and N_2 and that is the result in different production with different gas injection composition.

4.2 The optimum injection composition for specific coal rank

The objective of the study was to determine the optimum composition of CO_2 and N_2 in gas injection for each coal rank in order to maintain and improve methane production since different composition will have different methane production. The same procedures were applied on all coal rank. The following section presents the finding for specific coal rank.

4.2.1 Low rank coal

The simulation was done to determine methane total production versus time for low rank coal using different composition of gas. The results are as below.

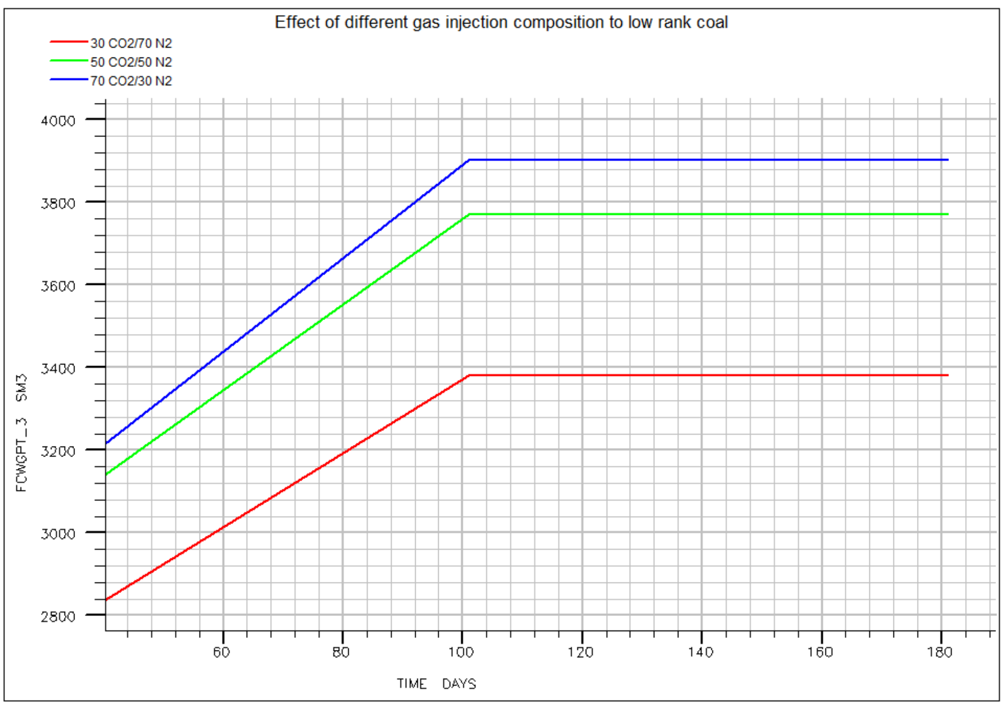


Figure 9: Methane Production vs Time for different composition of gas injection- low rank

From figure above, the methane production increase as the gas injection having higher composition of carbon dioxide gas. Table below summarize the total methane production for every injection composition for low rank coal.

Table 6: Total production of methane for different composition of gas injection- low rank

Compositon of gas injection (%)	30 CO_2/70 N_2	50 CO_2/50 N_2	70 CO_2/30 N_2
Total production of methane (sm^3)	3380	3771	3901

As refer to table above gas injection with 70% CO_2 and 30% N_2 gives the highest methane production where the total production is 3901 sm^3. Therefore for low rank of coal, 70 CO_2/30 N_2 is the optimum injection composition.

4.2.2 Medium rank coal

The total production of methane versus time for medium coal rank is as figure below.

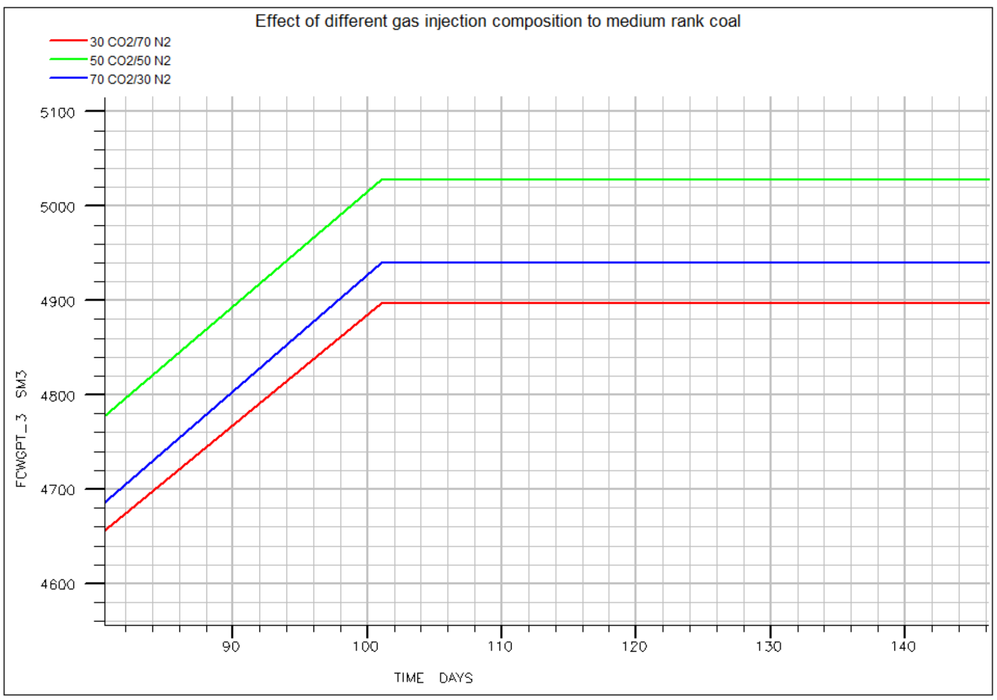


Figure 10: Methane Production vs Time for different composition of gas injection- medium rank

Based on the figure above, it shows that the total production of methane was the highest at composition of 50%CO_2/50%N_2. While for composition of 30%CO_2/70%N_2 and 30%CO_2/70%N_2 does not show much varies in the production of methane. For medium coal rank, it shows that equal composition of CO_2 and N_2 help in improving the production than having one higher composition than other. Table below summarize the total methane production for every injection composition for medium rank coal.

Table 7: Total production of methane for different composition of gas injection- medium rank

Compositon of gas injection (%)	30 CO_2/70 N_2	50 CO_2/50 N_2	70 CO_2/30 N_2
Total production of methane (sm^3)	4896	5027	4940

From the result, the methane production for composition of 50% CO_2 and 50% N_2 is 5027 sm^3. Therefore for medium coal rank injecting composition of 50% CO_2 and 50% N_2 seems to be the optimum. Comparing with low rank coals, higher N_2 content is required for higher coal rank to maximize the ECBM.

4.2.3 High Rank Coal

Below is the result for the total production of methane versus time for high coal rank.

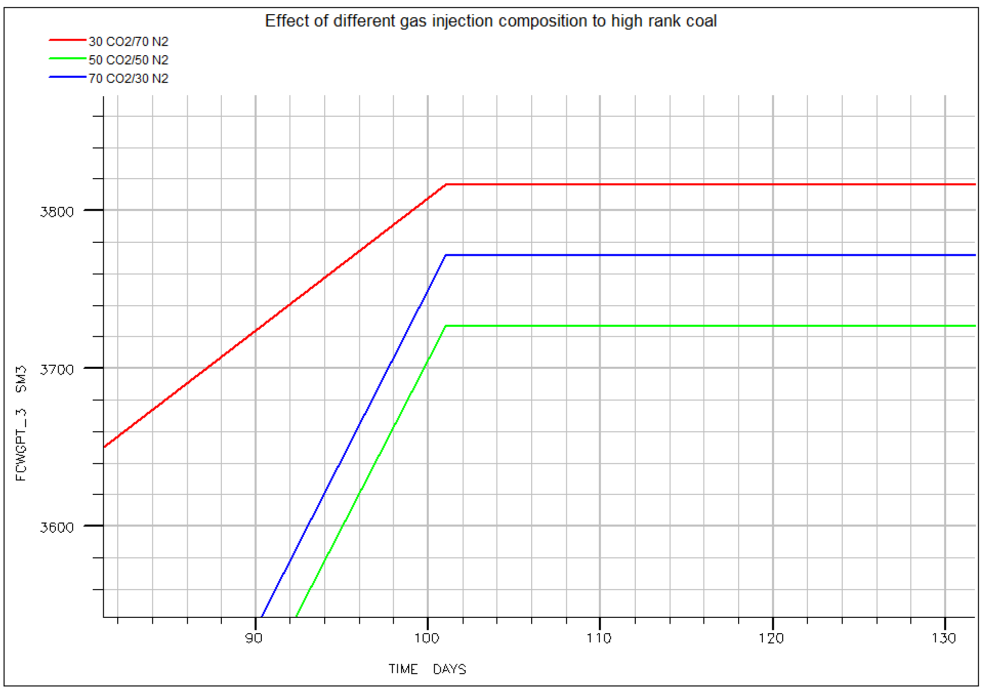


Figure 11: Methane Production vs Time for different composition of gas injection- high rank

Based on the graph above there is no much different result for methane production by injecting different composition of gas but the production rate of methane is faster and higher when injecting gas with more composition of nitrogen. From here, it can be said that CO_2 injection does not seem to apply well to the high rank coal compared to other coal rank.

Table 8: Total production of methane for different composition of gas injection- high rank

Composition of gas injection (%)	30 CO_2/70 N_2	50 CO_2/50 N_2	70 CO_2/30 N_2
Total production of methane (sm^3)	3814	3726	3771

From the result, 30% CO_2 and 70% N_2 injection seems to be the best option for high coal rank with methane production of 3818 sm^3. Therefore the optimum composition for high rank coal is 30% CO_2/70% N_2

4.2.4 Discussion for optimum gas injection composition for specific coal rank

Table below summarize the optimum gas injection composition for all coal rank.

Table 9: Summary of optimum injection composition for specific coal rank

Rank of coal	Optimum gas injection composition (%)	Total production of methane (sm^3)
Low rank	70 CO_2/30 N_2	3901
Medium rank	50 CO_2/50 N_2	5027
High rank	30 CO_2/70 N_2	3814

A trend seems to be appeared as coal rank increases, more nitrogen is necessary to improve the ECBM which is from 30% for low rank coals to 70% for high rank coal.

According to the theory, CO_2 molecule is larger than methane therefore it tends to swell the coal even more as it replaces methane in the coal. Low rank coals have high porosity with more compressible pore system (Cp). On the other hand as gas content is low due to an early stage coalification, the matrix for low rank coal is less likely to swell or shrink which this result in low rank coal having lower matrix compressibility (Cm). Therefore, low rank coal can accept CO_2 more than other coal rank thus less nitrogen is needed to enhance the methane production.

While for medium and high rank coal needed more nitrogen to enhance the methane production is because as the coal rank increases, pore compressibility is reduced and matrix compressibility increases. This means as the coal rank increase, it is more likely to swell or shrink by injecting CO_2.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Results from the simulation shows different injection composition does play a major role in ECBM processes as coal have different acceptance to carbon dioxide and nitrogen. Coal rank also does play a major role in ECBM processes as coal rank determines the maximum gas in place that could be stored per volume of coal, average permeability, average porosity, and matrix and pore compressibility which all this impacting the incremental of methane production.

The first part of the research shows that for all injection composition, medium rank gives the highest methane production with 4896 sm^3 for injection composition of 30 CO_2 / 70 N_2, 5027 sm^3 for injection composition of 50 CO_2 / 50 N_2, 4940 sm^3 for injection composition of 70 CO_2 / 30 N_2 which proves that medium rank coal is the best coal rank for CBM process. However as injecting different composition the methane production is also different for specific coal rank.

As the research goes by it shows that as coal rank increases, more nitrogen which is from 30% for low rank coals to 70% for high rank coal is needed to enhance the CBM recovery which this is due to the pressure dependent parameter varies between coal ranks.

As for recommendation, the simulation result can be improved by using real reservoir data instead of using ranges of theoretical value for the coal ranks. Different mixtures of gases could also be model to find the optimal solution as different types of gas have different effect to the ECBM processes. Besides, for more accuracy, the project can also continue by comparing the results with other simulator.

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APPENDIX

Grid system

Rectangular (x-y-z) grid system = 11x11x2

Area = 6 acres pattern

Pattern half width= 750.294 m

z-direction: 9 m

Operating Conditions

Well location:

- Injection well: (i=1, j=1, k=2)
- Production well: (i=11, j=11, k=2)

Well radius (2 7/8" well) 0.0365 m

Well skin factor = 0

181 day continuous N_2 and CO_2 injection/production period

Injection rate= 7079.205 sm^3/d

Maximum bottom hole pressure = 15,000 kPa

Maximum gas production rate = 100,000 m^3/d

Minimum bottom hole pressure = 275 kPa

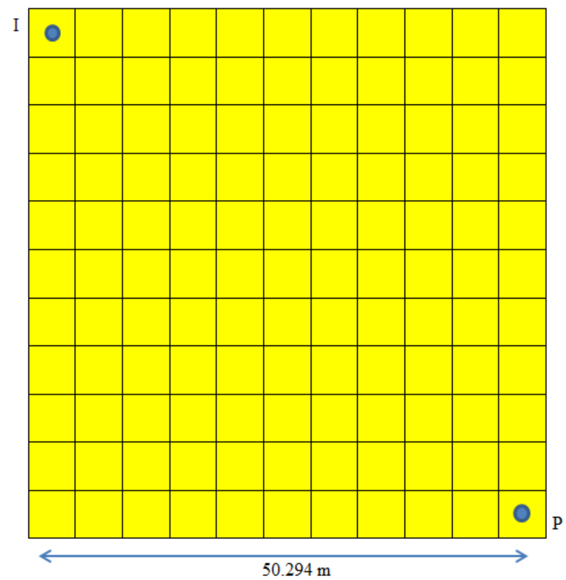
COALBED CHARACTERISTIC

Coalbed properties	**SI Units**
Coal seam thickness	9 m
Top of coal seam	1253.6 m
Initial Reservoir conditions	
Temperature	45^{o}C
Pressure (assumed uniform from top to bottom)	7650 kPa
Water properties at 45C	
Density	990 kg/m^3
Viscosity	0.607 cp
Compressibility	5.8x10^{-}7/ kPa

COALBED RESERVOIR AND ELASTIC PROPERTIES

Well spacing, acres	320
Seam depth, m	914.4
Net thickness, m	15.24
Initial reservoir pressure, kPa	10342.1
Initial water saturation, frac	0.95
Initial CO_2 composition, frac	0.1
Reservoir temperature, deg C	45
Young's modulus, kPa	2.9x10^{-6}
Poisson ratio	0.35

SCHEMATIC DIAGRAM OF GRID SYSTEM USED IN THE SIMULATIONS



VARIED INPUT PARAMETERS AND RANGES

Parameter	Min	Max	Unit
Density	641	929	kg/m^3
Average permeability	10	100	mD
Porosity	0.0025	0.01	-
PL CO_2	12.928	21.547	Bar
VL CO_2	0.032574884	0.051239447	sm^3/kg
PL N_2	72.398	120.663	Bar
VL N_2	0.00723884	0.018901413	sm^3/kg
PL CH_4	25.855	43.094	Bar
VL CH_4	0.018901413	0.042574884	sm^3/kg
Pore compressibility, Cp	2.90E-03	1.45E-02	1/bar
Matrix compressibility, Cm	1.48E-08	1.45E-04	1/bar
Carbon content	0.10	0.96	%