ISSN 1996-3343

# Asian Journal of Applied Sciences

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Asian Journal of Applied Sciences 7 (3): 158-168, 2014
ISSN 1996-3343 / DOI: 10.3923/ajaps.2014.158.168

# Effect of Coal Rank and Porosity on the Optimization of ECBM Recovery

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## ABSTRACT

Coal Bed Methane (CBM) is naturally occurring methane ($CH_4$) with small amounts of other hydrocarbon and non-hydrocarbon gases being adsorbed in coal seam reservoirs as a result of chemical and physical processes. CBM is often produced at shallow depths and often produced with large volumes of water at the early stage of production. There are several factors that influence the production of CBM like porosity, permeability, coal rank, initial gas content and natural fracture system. This study will be focusing on the effects of different coal ranks and coal porosity on the optimization of ECBM recovery ($CO_2$ injection). The injection of carbon dioxide ($CO_2$) will enhance the recovery of CBM and at the same time a very attractive option for $CO_2$ sequestration. This project is done by simulating the data of CBM basins obtained from available published research papers. A reservoir simulator ECLIPSE (E300) developed by Schlumberger will be used in this project. The results later will be compared and further analyzed to conclude the project outcomes. Based on the study and simulation that has been conducted, the outcomes of the result indicates that the higher coal rank will be having higher gas content whereas the porosity of coalbed may not be directly proportional to the increasing of burial depth. In certain cases, the less deep coalbed tend to has higher porosity compared to the deeper coal bed.

**Key words:** CBM, coal rank, porosity, methane, carbon dioxide, recovery

## INTRODUCTION

Coal has immense amount of surface area able to hold large volume of methane, since coal seams have large internal surfaces to store six to seven times more gas than the equivalent rock's volume in a conventional gas reservoir (USGS: Energy Resource Surveys Program, 2007). It consists mainly of methane ($CH_4$) with some amount of carbon dioxide, nitrogen, water vapor and heavier hydrocarbons like propane and butane. CBM is considered as "sweet gas" as it does not contain hydrogen sulphide ($H_2S$) (Alberta Energy, 2007).

According to Ham and Kantzas (2008), the total amount of CBM in-place reserves worldwide estimated to be between 3,500-95,000 Tcf. This made CBM to be considered as one of the largest unconventional resources of fossil fuel. In United States, total CBM in-place is estimated at 749 Tcf. As for Canada that has just begun producing gas from CBM, the estimated reserves are about 1,300 Tcf. As coal is a clean-burning energy source suitable for electricity generation, residential or commercial heating and vehicle fuel as in Compressed Natural Gas (CNG).

This study will be focusing on the effect of different coal ranks and porosity on the optimization of ECBM recovery. Different coal ranks are having different porosity with respect to their depth and maturity. By knowing the effective porosity, we will be able to predict the storage capacity of the coalbed and its natural gas content. It is the best to evaluate the potential of coal bed with respect to their coal rank and porosity in other to optimize the production of ECBM for marketable energy resource.

**Objective and scope of study:** The objectives of this study are:

- To study the effect of different coal rank on the optimization of ECBM recovery
- To investigate the impact of porosity on the optimization of ECBM recovery by using ECLIPSE (E300) simulator

The scope of study includes:

- Gathering data e.g., porosity, permeability, coal rank, coal bed depth from different CBM basins around the world
- Conducting a simulation by using ECLIPSE (E300) simulator base on the data gathered
- Analyzing the simulation results from ECLIPSE (E300) simulator

**Coal ranks:** The degree of ‘metamorphism’ undergone by a coal, as it matures from peat to anthracite which has an important bearing on the coal physical and chemical properties referred as the ‘rank’ of the coal. Low rank coals, such as lignite and sub-bituminous is typically softer, friable materials with a dull, earthy appearance. They have high moisture levels and low carbon content, thus also low energy content.

Higher rank coals are typically harder, often with black vitreous luster. Increasing in coal rank is alongside by a rise in the carbon and energy contents while the moisture content is decreasing. Anthracite is the top rank coal and has correspondingly higher carbon and energy content with lower level of moisture.

The concept of coal rank is used to indicate the stage of alteration attained by a particular coal; the greater the alteration, the higher the coal. The transformation of peat to coal known as “coalification” is geothermal process and being dependent upon the effects of heat and pressure acting over periods of time. Figure 1 shows the respective parameters of different coal ranks.

As the rank of coal increases, the maximum gas holding capacity will also increase. This is due to lesser moisture content and higher porosity of the coal. However, the relationship between coal rank and gas properties neither be straightforward nor universal as there might be a doubt that rank is primarily influence on the maximum gas holding capacity of coal. General thought is that the mature the coal, the higher gas content as stated by Hildenbrand *et al.* (2006) and Kim (1977).

**Porosity:** CBM is characterized by their unique dual porosity systems. They contain both primary (micropore and mesopore) and secondary (macropore) porosity systems (Law *et al.*, 2002). Methane ($CH_4$) is trapped in coal pores either as a free gas or adsorbed in the matrix pores of the coal (Tunio *et al.*, 2012). The primary porosity system contains the most of the gas-in-place while the secondary porosity system provides the channel or conduit for gas movement into the wellbore. Methane ($CH_4$) is mainly store in the primary gas storage by means of adsorption.

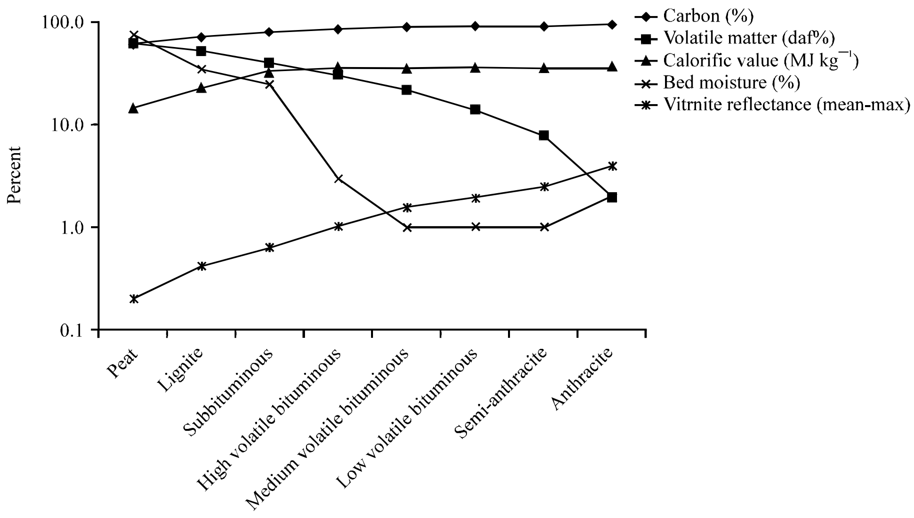

Fig. 1: Coal rank with respect to different parameters (Moore, 2012)

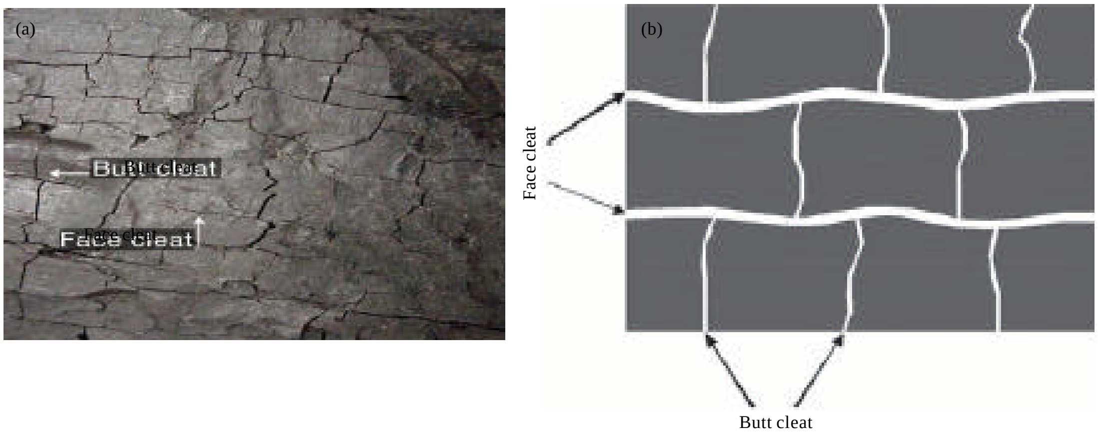

Fig. 2(a-b): Cleats of the coal seams (Underground Coal, 2013; Davidson *et al.*, 1995)

It is trapped inside the porous media of the matrix. The matrix is relatively impermeable due to its fine size and the gas movement is dominated by diffusion. The macropores or secondary storage is also known as the 'cleat'. It can be subdivided into the face cleat which is continuous throughout the coal bed and the butt cleat which is discontinuous and terminates at the intersections with the face cleat (Syahrial, 2005). Figure 2 shows the cleat orientation of the coal seams cleats.

**Estimated gas content:** Prediction of gas content in coal beds and the potential recovery has relied primarily on its relationship to coal's rank, pressure, temperature, moisture and ash content and methane adsorption capacity (Eddy *et al.*, 1982). During the transformation of peat to lignite, a large quantity of biogenic methane is produced. From sub-bituminous through high-volatile bituminous, an additional 31 cc g$^{-1}$ 1,000 cf ton$^{-1}$ of methane is generated. In the complete coalification of anthracite, 190-310 cc g$^{-1}$ (6-1,000 cf ton$^{-1}$) of methane is generated (Dolly and Meissner, 1977).

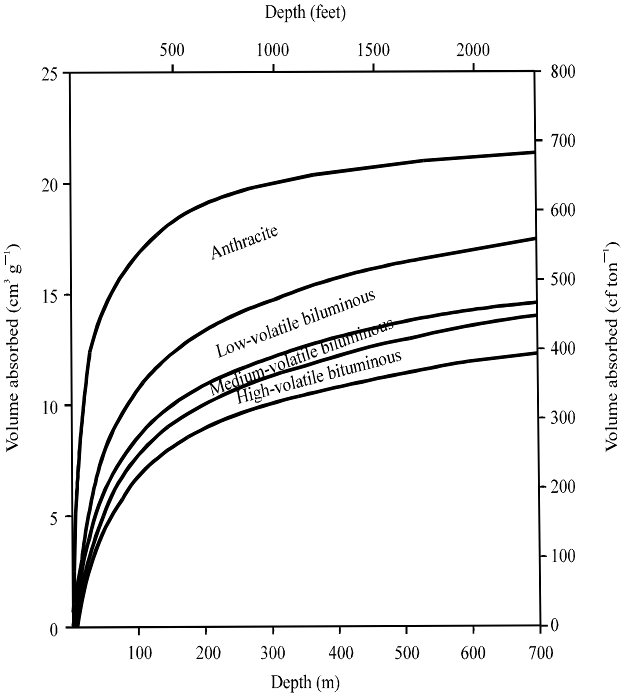

Fig. 3: Estimated $CH_4$ content according to depth and rank (Eddy *et al.*, 1982)

In order to estimate the gas content, the adsorption capacity of specific rank of coal must be identified by constructing adsorption isotherms curves. These curves as shown in Fig. 3 were redrawn by Kim (1977) after correcting the temperature, ash and moisture content and depth of burial was equated to pressure.

**CBM recovery process:** The conventional primary CBM recovery process often begins with a production well that is often stimulated by hydraulic fracturing to connect the wellbore to the natural fracture of coal seams via., the induced fracture created. In order for methane to be released and flow to take place, water is first pumped out from the well. The flow of water will decrease the pressure in the cleats thus making coal less capable of retaining methane in adsorbed form. Gas and water begin to move through the natural and induced fractures in the direction of decreasing pressure. As the natural fracture system pressure drops, gas molecules desorbed from the primary-secondary porosity interface and released to the secondary porosity system. The adsorbed gas concentration in the primary porosity near the natural fractures is reduced. A concentration gradient is established between the cleats and coal matrix which results in mass migration of methane by means of diffusion through the microporosity and mesoporosity.

Although, the method quite simple, the estimated total methane recovery only around 50%. Hence, Enhanced Coal Bed Methane (ECBM) techniques have been developed to recover more portion of Gas-In-Place (GIP). According to Mitra and Harpalani (2007) these techniques involve injecting another gas into the coal reservoir. The process can either be CO2-ECBM where $CO_2$ displaces adsorbed methane from the coal matrix blocks, or $N_2$-ECBM where $N_2$ strips methane from coal matrix by reducing the partial pressure in the cleat system.

**Carbon dioxide ($CO_2$ injection):** $CO_2$ has higher sorptive affinity than $CH_4$. When $CO_2$ is injected into the coal natural fracture system during Enhanced Coal Bed Methane (ECBM) recovery process, it is more preferably to be adsorbed into the primary porosity system. The $CO_2$ drives $CH_4$ from the primary porosity into the secondary porosity system. The secondary porosity pressure then increased due to the $CO_2$ injection, thus forced the $CH_4$ flows into the production well to be produced. The $CO_2$ is stored in-situ and is not produced unless the injected gas reaches the production well. This process basically is terminated when $CO_2$ breakthrough occurs.

## METHODOLOGY

**Description of CBM simulator:** This study follows work done by Law *et al.* (2002). However, the numerical simulator used in this study is only E300 compositional simulator which follows black oil characteristics with additional features for CBM modeling and only capable to handle two gas components (e.g., $CH_4$ and $CO_2$ only). ECLIPSE does not incorporate the extended Langmuir isotherm theory in the CBM model. However, it has a feature of relative adsorption for each gas component. This allows the simulator to take into account the “non-ideal” adsorption behavior of the two-gas mixture. Five different CBM basins have been selected to be tested in this study. The properties of each basin are recorded in Table 1.

**Description of test problem set:** The reference set used is $CO_2$-ECBM recovery process in an inverted five-spot pattern (Fig. 4). The basic features of E300 simulator are as follow:

- Darcy flow of gas and water in the natural fracture system in coal
- Adsorption/desorption of two different gas components ($CH_4$+$CO_2$) at the coal surface
- Instantaneously gas flow (diffusion) between the coal matrix and natural fracture system
- No coal matrix shrinkage/swelling due to gas desorption/adsorption
- No compaction/dilation of natural fracture system due to stresses
- No non-isothermal adsorption due to difference in temperatures between the coal bed and injected $CO_2$

For each basin, 10 different porosity values are defined in the simulator to observe the behavior of $CH_4$ production rate when the porosity is changing in increasing order. A complete description of the test problem set is given in Appendix A.

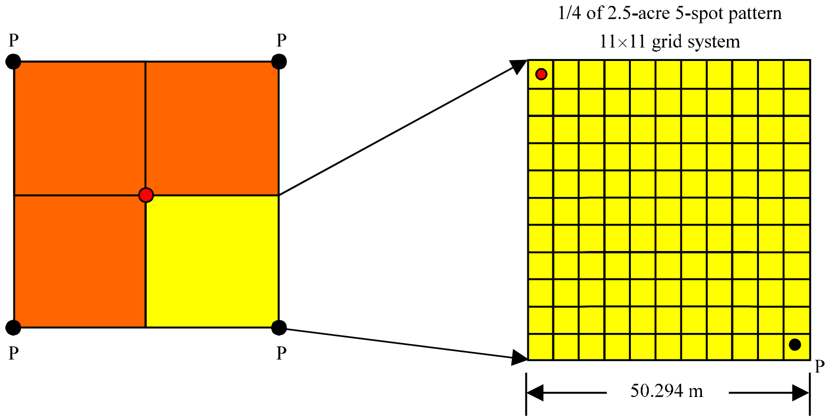

Fig. 4: Schematic diagram of five-spot pattern (Law *et al.*, 2002)

Table 1: Data from different CBM basins modified from (Syahrial, 2005; Mavor *et al.*, 2003; Sinayuc and Gumrah, 2008; Van Wageningen and Maas, 2007; Zheng and Xue, 2012)

| | Parameters | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CBM Basin | Coal rank/quality | Initial water saturation | Coal depth (ft) | Porosity (tested) | Permeability (mD) | Coal density (g $cm^{-3}$) | Initial reservoir temperature (°F) | Initial reservoir Pressure (psia) |
| San Juan (United States) | Sub-bituminous | 0.408 | 4,112.8 | 0.001-0.010 | 3.65 | 1.43 | 113 | 1,109.5 |
| Powder River (United States) | Sub-bituminous C | 0.408 | 557 | 0.001-0.010 | 10 | 1.33 | 113 | 152.5 |
| Qinshui (China) | Anthracite | 0.08 | 457.2 | 0.01-0.10 | 3.0 | 1.60 | 131 | 2,000 |
| Zonguldak (Turkey) | High-volatile A abituminous | 0.01 | 1,788 | 0.01-0.10 | 8.0 | 1.54 | 94 | 1500 |
| Upper Silesian (Poland) | High-volatile bituminous | 0.10 | 3,280 | 0.001-0.010 | 1.3 | 1.30 | 90 | 1300 |

**Appendix A**

**Problem set:** 5-spot $CO_2$-ECBM recovery process
**Grid system:** Rectangular (x-y-z) grid system; 11×11×1 (Fig. 4)

Area = ¼ of a 2.5 acres pattern
Pattern half width = 50.294 m [165 ft]

Operating Conditions
Well locations:
Injection well: (i = 1, j = 1, k = 1 )
Production well: (i = 11, j = 11, k =11)
Well radius (2 7/8" well): 0.0365 m [0.11975 ft]
Well skin factor = 0

182.5-day continuous $CO_2$ injection/production period (0-182.5 days):

- $CO_2$ injection rate (full well) = 23, 316.82 $sm^3$ $day^{-1}$ [$1\times10^6$ scf $day^{-1}$]
- Maximum bottom-hole pressure = 15, 000 kPa [2175.6 psia]
- Minimum bottom-hole pressure = 25 kPa [39.885 psia]

## RESULTS AND DISCUSSION

Figure 5 shows comparisons of $CH_4$ production rates for primary CBM (zero injection) and $CO_2$-ECBM recovery as functions of time for San Juan basin. It shows the enhancement in the $CH_4$ production due to the $CO_2$ injection. Generally, the enhancement of $CH_4$ recovery remains until $CO_2$ breakthrough occurs in the production. In this case, the $CO_2$ is continuously injected for 182.5 days. Due to higher initial gas saturation in every basins, the typical "negative decline" in $CH_4$ production rate in primary CBM recovery process due to "dewatering" process is not clearly observed in this case.

The results of other basins are shown in Fig. 6-9, respectively. The production data for each basin is also recorded in Table 2 and 3. All well data presented are on a full-well basis and pattern results for the full 5-spot pattern consisting of four one-quarter producers and one full injector (Fig. 4).

Table 2: Production data of CBM basins (porosity 0.001-0.01)

| Porosity value | $CH_4$ production rate ($sm^3$ $day^{-1}$) | | | Total $CH_4$ production ($sm^3$) | | |
|---|---|---|---|---|---|---|
| | San juan | Powder river | Upper Silesian | San juan | Powder river | Upper Silesian |
| 0.001 | 5116-0.2 | 363-0.1 | 9151-107 | 5116-238,842 | 363-65,809 | 9151-396,919 |
| 0.002 | 4845-0.3 | 341-0.1 | 9097-110 | 4845-239,297 | 341-65,820 | 9097-398,580 |
| 0.003 | 4717-1.3 | 330-0.1 | 9079-116 | 4717-239,778 | 330-65,852 | 9079-399,896 |
| 0.004 | 4639-1.1 | 322-0.2 | 9072-120 | 4639-240,262 | 322-65,877 | 9072-401,215 |
| 0.005 | 4584-1.7 | 317-0.3 | 9071-124 | 4584-240,707 | 317-65,896 | 9071-402,539 |
| 0.006 | 4543-2.4 | 313-0.4 | 9073-128 | 4543-241,165 | 313-65,901 | 9073-403,877 |
| 0.007 | 4510-3.0 | 311-0.2 | 9079-132 | 4510-241,619 | 311-65,939 | 9079-405,204 |
| 0.008 | 4483-3.8 | 309-0.2 | 9086-135 | 4483-242,082 | 309-65,950 | 9086-406,571 |
| 0.009 | 4461-4.7 | 307-0.3 | 9094-139 | 4461-242,540 | 307-65,974 | 9094-407,911 |
| 0.010 | 4442-5.4 | 305-0.3 | 9103-142 | 4442-243,008 | 305-65,990 | 9103-409,273 |

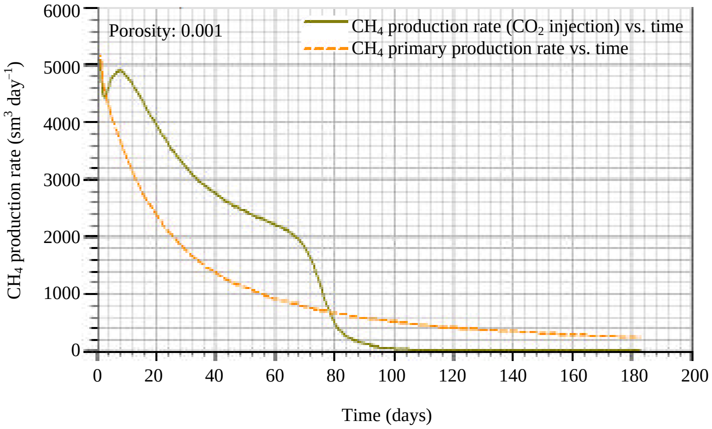

Fig. 5: San juan basin

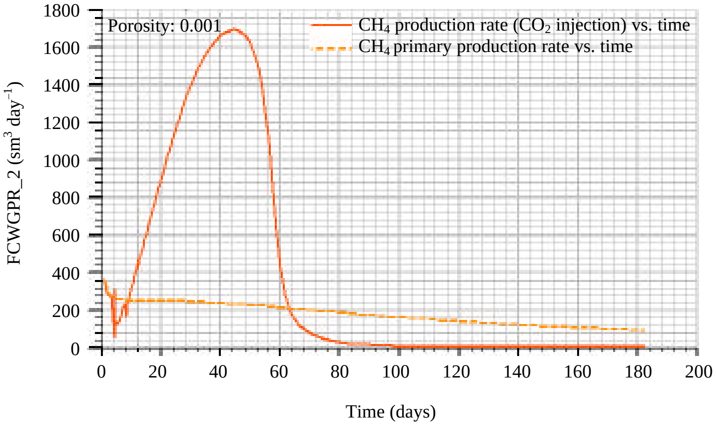

Fig. 6: Powder river basin

Table 3: Production data for CBM basin (porosity 0.01-0.1)

| Porosity value | $CH_4$ production rate ($sm^3\ day^{-1}$) | | Total $CH_4$ production ($sm^3$) | |
|---|---|---|---|---|
| | Qinshui | Zonguldak | Qinshui | Zonguldak |
| 0.01 | 25,000-267 | 25,000-1.6 | 25,000-1,095,616 | 25,000-349,259 |
| 0.02 | 25,000-291 | 25,000-2.0 | 25,000-1,112,601 | 25,000-371,176 |
| 0.03 | 25,000-315 | 25,000-2.3 | 25,000-1,129,681 | 25,000-392,963 |
| 0.04 | 25,000-338 | 25,000-2.7 | 25,000-1,146,527 | 25,000-414,737 |
| 0.05 | 25,000-362 | 25,000-3.2 | 25,000-1,163,427 | 25,000-436,569 |
| 0.06 | 25,000-387 | 25,000-3.7 | 25,0001,80,193 | 25,000-458,374 |
| 0.07 | 25,000-412 | 25,000-4.3 | 25,000-1,197,189 | 25,000-480,232 |
| 0.08 | 25,000-437 | 25,000-5.0 | 25,000-1,214,052 | 25,000-502,002 |
| 0.09 | 25,000-463 | 25,000-5.7 | 25,000-1,230,457 | 25,000-523,812 |
| 0.10 | 25,000-489 | 25,000-6.5 | 25,000-1,247,108 | 25,000-545,638 |

Base on the results shown above, the initial $CH_4$ production rate for San Juan (Sub-bituminous) basin is decreasing as the porosity value increased from 0.001-0.01. However,

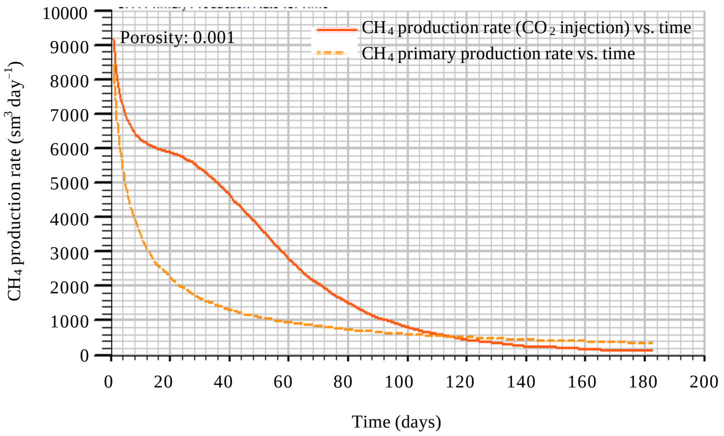

Fig. 7: Upper silesian basin

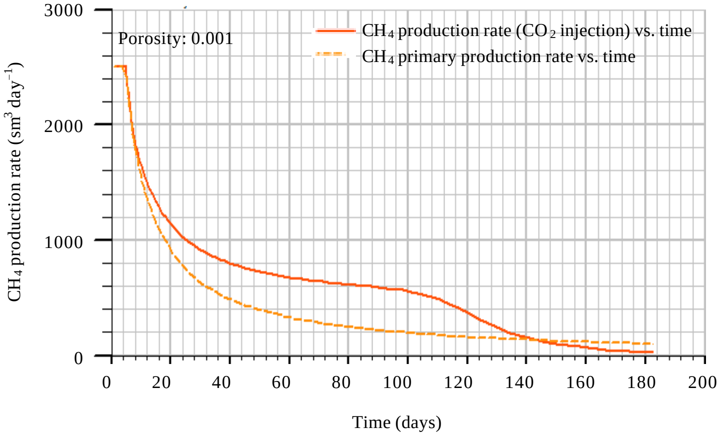

Fig. 8: Qinshui basin

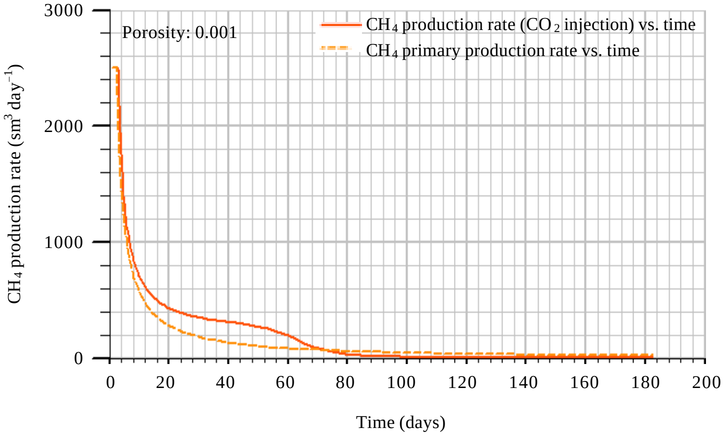

Fig. 9: Zonguldak basin

the final production rate is increased and the total production of $CH_4$ is also increased. The Powder River basin also shows the same trend as San Juan, however the production rate and total production is lower than San Juan. This is because Powder River basin has lower coal rank than San Juan basin which is Sub-bituminous C.

As for Upper Silesian basin, with coal rank of High-volatile bituminous the initial production rate slightly decreased from porosity value 0.001-0.005. Later on, the initial production rate increased until porosity value of 0.01. The final production rates keep on increasing as well as total $CH_4$ production.

Qinshui and Zonguldak basins have the same initial production rate for each porosity values (0.01-0.10). The only different is the final production rate for Qinshui basin is higher than Zonguldak basin, although both of their rates increased. This is due to the Anthracite coal of Qinshui basin which is the highest rank, compared to High-volatile A bituminous of Zonguldak basin. The total $CH_4$ production for both basins are increased.

The methane ($CH_4$) production from CBM reservoir can be enhanced and optimized by means of injecting Carbon dioxide ($CO_2$) to recover more gas. CBM reservoir with high porosity value and high coal rank is the excellent candidate for greatest methane ($CH_4$) production by using $CO_2$ injection.

## CONCLUSION

From this study, it shows that as the porosity value increases, the production rate and total production of $CH_4$ will also increases for all basins. However, this effect is very significant in higher coal rank reservoir which gives the highest production. The highest production of $CH_4$ is from Qinshui basin, follows by Zonguldak, Upper Silesian, San Juan and Powder River as the least production which follows the decreasing of coal rank from anthracite, high-volatile A bituminous, high-volatile bituminous, sub-bituminous and sub-bituminous C. In real condition the porosity of CBM reservoir usually ranging from 0.1-10%. Therefore, the objectives of this study are achieved.

## RECOMMENDATIONS

This study can be further improved by using basins with lower coal rank e.g., peat and lignite to achieve a wide range of results. Besides, available data from other CBM basins with the same coal rank in this study can be used and tested to make a comparison. Other available simulators can also be used like CMG, GEM, COMET2, SIMED II, GCOMP etc. Later the results from each simulator can be made as a comparison study. This will help to verify the reliability or consistency of the test results. Other than that, experimental study also can be performed to test the coal samples of related ranks.

## ACKNOWLEDGMENT

The authors would like to thank Universiti Teknologi PETRONAS for giving support and opportunity to conduct this study.

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