DEVELOPMENT OF MODEL FOR METHANE FLOW IN COAL AS POROUS MEDIA

***Dagde, K. K., and Ehirim, E. O.**
Department of chemical/petrochemical engineering
Rivers state university of science and technology,
Port Harcourt, Rivers State, Nigeria.
dagde.kenneth@ust.edu.ng

ABSTRACT

The primary objective of this work is to develop a model capable of predicting the single-phase flow of methane through coal as a porous media. The model was developed by applying the principle of conservation of mass on a controlled volume of coal seam and incorporating the Darcy's law for laminar flow of methane. The model was solved numerically using implicit formulation of Finite Difference method. The result was validated with literature data. Predictions were made on the sensitivity of the model by varying parameters such as permeability, cleat distance, temperature, permeability, porosity, viscosity and the partial pressure. The result obtained showed that an increase in permeability led to an increase in effective stress and decrease in flow rate. Permeability and porosity are flow characteristics that influence fluid flow through its pores. The result also indicated that permeability is highly dependent on the applied gas pressure and the rock stress. The model will aid the extraction of methane for economical recovery and use, as well as underground mine degassing for safety reasons and also can be integrated into existing reservoir simulator to predict the variability of reservoir properties and how operating parameters affect performance under real conditions.

Keywords: *Modeling, Coal seam, Porous Media, Darcy's Law, Permeability, Partial Pressure.*

1.0 INTRODUCTION

Substantial amount of methane rich gas are generated and stored in coal formation. The coalification process whereby plant material is progressively converted to coal generates large quantity of methane rich gas, which is stored within the coal structure. In the process of coalification, coals increase in rank from lignite to sub-bituminous, bituminous and anthracite. Coal rank directly influences the gas (methane) storage capacity of coal. The type of organic material, depositional setting, pH, temperature, reducing potential depth of burial and time of burial influence the rank and type of coal formed(Saulsberry *et al.,* 1996). Most commercial coal bed methane is domicile in coals within the rank range of sub-bituminous to low volatile bituminous coal. Coal of this rank usually provides optimum gas (methane) content and natural permeability. The lignite, anthracite and graphite rank are usually low in methane gas because of its extremely low permeability, the lignite has high porosity while the anthracite and graphite are of low porosity and high volatile components drive off (Alpern and Lemos de Sousa, 2002). The presence of this gas has been recognized due to explosion and outburst associated with underground mining [Harpalani and Schraufnagel, 1990]. The recovery process of methane in coal begins with a production well that is often stimulated by fracturing to connect the well bore to the coal natural fracture system through an induced fracture [Mazumder *et al.,*. 2001]. There are two types of fractures that occur in coal, these are termed butt cleat and face cleats. Face cleats develop first and tend to be more continous than butt cleats. Butt cleats usually form at right angle to face cleats and are discontinuous, resulting in lower permeability (Harpalani and Schraufnagel, 1990). When the pressure in the well is reduced by pumping water from the well using artificial lift mechanism, the pressure in the induced fracture is reduced which in turn reduces the pressure in the natural coal fracture system. Initially, when the natural coal fracture system pressure drops the critical desorption pressure, methane starts to desorp from the primary-secondary porosity interface and is released into the secondary porosity system [Andersen, 2003]. As a result, the absorbed gas concentration is the primary porosity system near the natural fractures is reduced. This reduction creates a concentration gradient that result in mass transfer by diffusion through the micro and meso porosity [Mazumder *et al.,* 2001]. Adsorbed methane continues to be released as the pressure is reduced. Methane is extracted from coal mines to majorly reduce its emissions which causes mine explosion and for use as a clean source of fuel [Hargraves, 1984].

The need for reservoir models that can predict and evaluate production capability of coal gas is apparent. There are many models of reservoir available.of which Karacan *et al.*, (2011; 2007) presented the Finite Element Method Laboratory (FEMLAB) technique for improving gas management in coal mines. Wang (2003) also used the Computational Fluid Dynamic (CFD) modeling technique in investigating the significance of ventilation and gas management during coal mining. Curl (1978) and Hargraves,(1984) have given detailed reviews on the nature and characteristics of methane content in coal seams. Lama and Nguyen (1987) conducted diffusion test, permeability test, desorption test on a cylindrical specimen to determine flow of methane. Wide spread utilization of coal bed methane model has established the tools for analyzing and estimating production from coal bed methane mines. It is the aim of this study to predict the single-phase flow of methane through coal as a porous media [Harpalani & Schraufnagel, 1990]. In this study, a model is developed for the extraction of methane for economical recovery and use, as well as underground mine degassing for safety reasons and also can be integrated into existing reservoir simulator to predict the variability of reservoir properties and how operating parameters affect performance under real conditions. Numerical MATLAB technique was adopted for simulation.

2.0 MODEL DEVELOPMENT

Figure 1 depicts a hypothetical representation of coal cleat with continuous methane flow across its boundary. Methane molecules absorbed from the sites, *diffuse through the coal matrix till they find a cleat [Harpalani & Zhao, 1991]. After entering the cleat system, this flow follows the Darcy's law and come out. The coal bed is made up of small cubic blocks separated by fractures. The spacing of the fractures determines how far the methane has to diffuse before reaching the fracture and the dimension of the fracture decides the quantity of methane that can flow through [Harpalani *et al.*, 1990]. The one dimensional, coal matrix is considered as a prism. This methane diffuse through micro pores and meets the cleats [Gamson et al., 1992]. These cleats allow it to flow to the bore well.

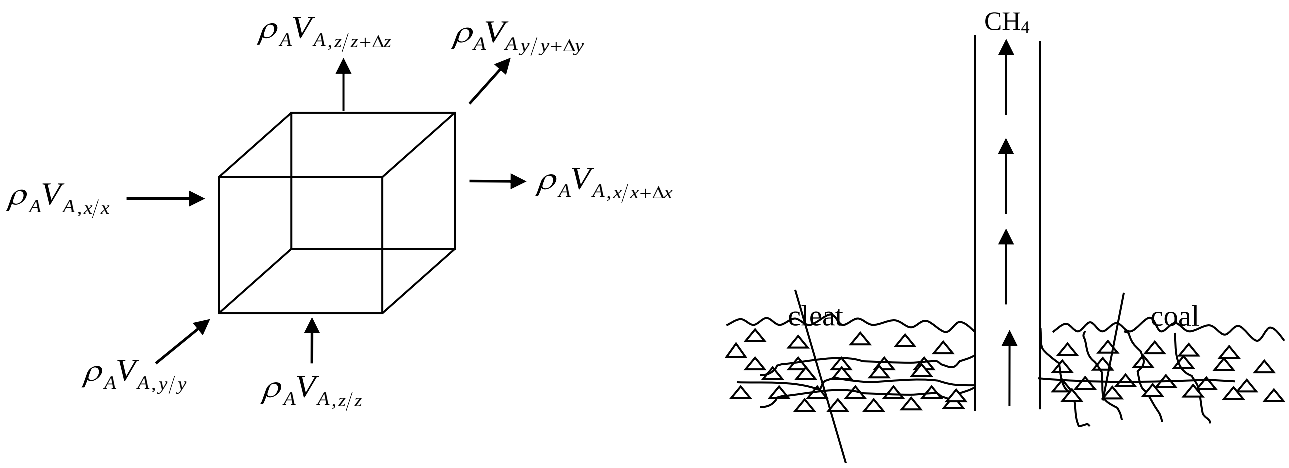

Figure 1A & B: Hypothetical representation of coal body with flow of methane gas

where ρ_A is the density of methane, $V_{A,x,y,z}$ is the velocity of methane in the x, y, z direction respectively, the methane enters at point x, y or z and exists at $x+\Delta x$, $y+\Delta y$ and $z+\Delta z$ respectively.

2.1 Model Assumptions

In the derivation of the model, the following assumptions are made:

1) The flow of methane inside the cleats is considered as laminar and hence Darcy's law is applicable (Lama and Nguyen, 1987; Wang, 2013).
2) The coal body is a rectangular prism.
3) Gravitational effects are negligible
4) The effect of diffusion is neglected in the cleats.
5) Isothermal condition is assumed during degasification process

6) The width and cleat spacing remains constant during the gas flow period
7) No accumulation of methane at the fracture surface.
8) During desorption of methane there exists no matrix shrinkage.
9) Permeability is assumed to be constant while it varies as per the Klinkenberg Law (Lama and Nguyen, 1987). .

Under these conditions, the general relation for mass balance of methane flow in and out of the control volume for a rectangular prism without chemical reaction may be stated as:

[net rate of mass efflux of methane for control volume] + [net rate of accumulation of methane within the control volume] = 0 (1)

Defining each term and substituting appropriate variables into equation (1) yields:

$$\frac{\partial \rho_A V_{A,x}}{\partial x} + \frac{\partial \rho_A V_{A,y}}{\partial y} + \frac{\partial \rho_A V_{A,z}}{\partial z} + \frac{\partial \rho_A \phi}{\partial t} = 0 \qquad (2)$$

Assuming that methane is flowing in z-direction only; we have

$$\frac{\partial \rho_A V_{A,x}}{\partial z} + \frac{\partial \rho_A \phi}{\partial t} = 0 \qquad (3)$$

The flow of methane in coal as porous media follows the Dancy's law which states that the flow rates of a fluid through a porous media is proportional to the partial pressure gradient; thus:

$$V_{A,Z} = -\frac{kA}{\mu}\frac{\partial P_A}{\partial z} \qquad (4)$$

Recall that one mole of methane contains a mass equivalent to its molecular weight; thus

$$\rho_A = C_A \; M_A \qquad (5)$$

$$C_A = \frac{P_A}{RT} \qquad (6)$$

therefore,

$$\rho_A = \frac{P_A M_A}{RT} \qquad (7)$$

Substituting equation (3) and (6) into equation (2) gives

$$\frac{\partial}{\partial Z}\cdot\left[-\frac{\rho_A KA \, \partial P_A}{\mu . \partial Z}\right] + \frac{\partial}{\partial t}\left[\frac{M_A P_A}{RT}\right]\phi = 0 \qquad (8)$$

$$-\rho_A \frac{KA}{\mu}\cdot\frac{\partial^2 P_A}{\partial Z^2} + \frac{\phi M_A}{RT}\frac{\partial P_A}{\partial t} = 0$$

let $\rho_A \dfrac{KA}{\mu} = \alpha$ and $\dfrac{\phi M_A}{RT} = \beta$

$$-\alpha \frac{\partial^2 P_A}{\partial Z^2} + \beta \frac{\partial P_A}{\partial t} = 0$$

$$\frac{\partial^2 P_A}{\partial Z^2} = \frac{\beta}{\alpha} + \frac{\partial P_A}{\partial t} \qquad (9)$$

Hence, $$\frac{\partial^2 P_A}{\partial Z^2} = \left[\frac{\phi M_A}{RT}\cdot\frac{\mu}{K\rho_A A}\right]\frac{\partial P_A}{\partial t} \qquad (10)$$

where K is the permeability of the fluid, μ is the viscosity of the fluid, A is the cross- sectional area of the cleat, R is the universal gas constant, t is the absolute temperature, M is the molecular weight of methane.

Equation (9) represents the model for the methane flow in coal as porous media.

2.2 Solution Technique and Operating Parameters

Equation (9) with the respective boundary conditions P(x,0)= 7.5mpa, and P(0,t)= P_0 was solved numerically using implicit formulation of Finite Difference method. The following operating parameter obtained from literature was used for the simulation.

PARAMETERS (UNIT)	VALUE
Temperature (T)	293K
Viscosity (µ)	1.081 x 10^{-5}NS/m^2
Initial Pressure (P_0)	101.325 kPa
Porosity (Ø)	0.025
Universal Gas Constant (R)	8314J/kmol.K
Molecular Weight of methane gas(MA)	16.043
Permeability of the matrix (k)	2.47 x $10^{-15}$$m^2$
Density of matrix (ρ)	1370kg/m^3

3.0 RESULTS AND DISCUSSION

3.1 Variation of partial pressure of methane with cleat distance at permeability k =2.47e-15; porosity φ= 0.025

Figure 2 shows a plot of the methane gas pressure against the Cleat distance for a permeability of 2.47e-15 and porosity of 0.025 at different times. There is a fast decrease in pressure in all times within 28 meters of the Cleat. This amounts to the release of more methane gas within this region of the Cleat.

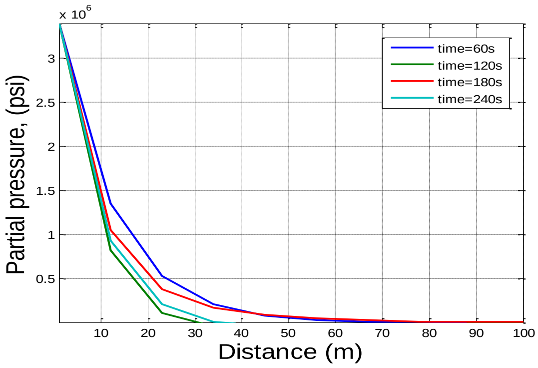

Figure 2. Methane gas pressure against Cleat Distance for Permeability k = 2.47e-15 and Porosity φ= 0.025

It was also observed that there was a very small decrease in the pressure after about 80 meters of the Cleat. This could arise due to the small amount of the methane gas occupying this region of the Cleat.

3.2 Effect of porosity on partial pressure of methane with cleat distance at permeability k =1.47e-15; porosity φ= 0.025

Figure 2 shows a graph of the partial pressure of methane for about 10% decrease in the permeability of the system. A close observation showed that, even though there was no noticeable change in the partial pressure of the gas, as compared to Figure 1, the amount of the gas released was smaller.

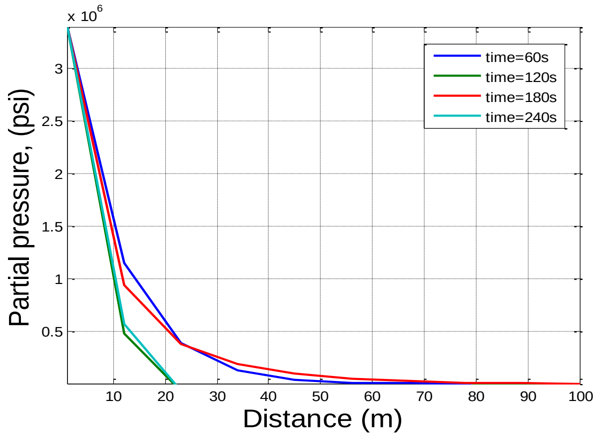

Figure 3. Gas pressure against Cleat distance for Permeability k =1.47e-15; Porosity φ= 0.025

This observation demonstrated that the permeability of the system plays important role when the flow or release of the methane gas from the Cleat was considered. High permeability allows for large extraction of the gas from the coal seams.

3.3 Effect of Porosity Partial Pressure of Methane with Cleat Distance at Permeability k =2.47e-15; Porosity φ= 0.020

For a 10% reduction in the matrix porosity, the partial pressures of the gas at different times are very distinct, as Figure 3 showed. This graph also illustrated that within 10 meters of the Cleat, the amount of the flue gas was almost the same, independent of the time in simulation. After about 12 meters, the release of the gas became a function of time.

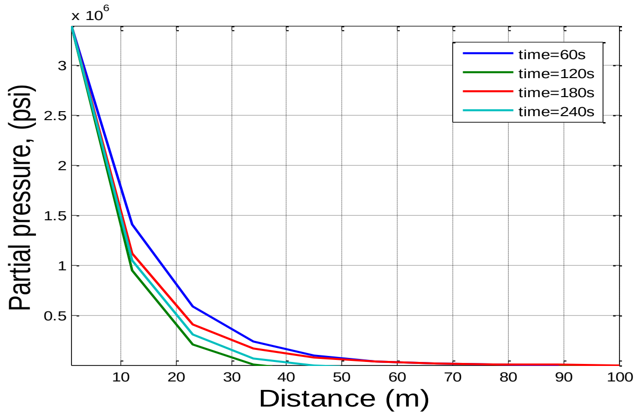

Figure 4.. Partial pressure of methane gas against Cleat distance for permeability K=2.47e-15 and Porosity φ= 0.020

That is to say that more gas was released after 240s. Furthermore, the production of methane was independent of Cleat distance after 70 meters for all the time simulated.

3.4 Effect of Viscosity on Partial Pressure of Methane with Cleat Distance at Permeability k =2.47e-15; Porosity φ= 0.020

The production of pure methane could be achieved by the decrease in the viscosity of the gas. That would mean that there was no impurity coming along with the gas.

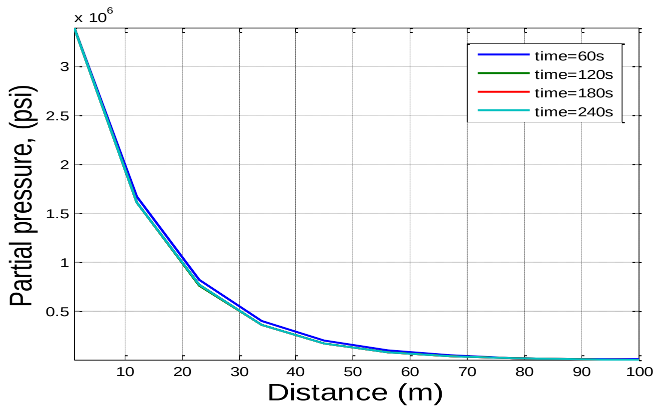

Figure 5. Methane pressure vs Cleat distance for K = 2.47e-15, φ=0.02, μ = 1.081e-6 (10% decrease)

If this assumption was considered true scientifically, then Figure 5 could be considered correct. This figure showed that the production of pure methane gas was independent of the simulation time. This illustrated that the same amount of methane was produced irrespective of the time of operation.

3.4 Effect Of Temperature on Partial Pressure of Methane With Cleat Distance at Permeability K =2.47e-15; Porosity Φ= 0.020

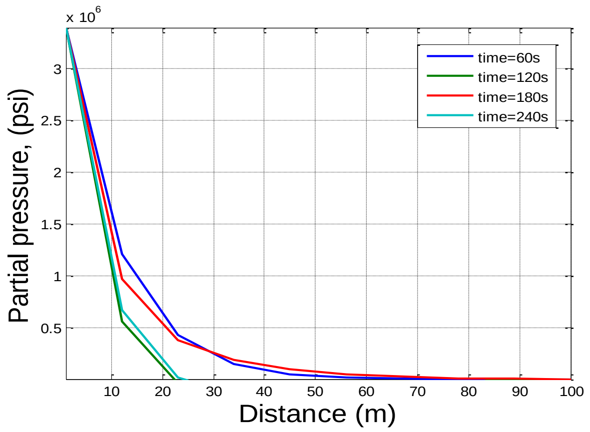

Figure 6. Methane gas pressure Vs Cleat distance for T=313K, k=2.47e-15, μ= 1.081e-5, and φ = 0.02

An increase in temperature did not alter the behavior of the system. However, it was observed that there was a little distortion of gas flow from the Cleat if the temperature was further increased above 313K. This result is in agreement with work done in literatures (Karacan *et al.,* 2011; 2007; Wang, 2013)

4.0 CONCLUSION

This work has demonstrated that more of the methane gas was released from the Cleat base when there is an increase in the partial pressure of the gas in question. The effect of parameters such as permeability, cleat distance, temperature, permeability, porosity, viscosity and the partial pressure were investigated. The results revealed that an increase in temperature did not affect the behavior of the system but however if the temperature rises above 313K there will be changes in its behavior. It was also observed that at 10% decrease in porosity, the changes in the behavioral pattern of the partial pressure of methane gas are almost negligible. The proposed model considered only laminar flow applying Darcy's law and can be applied to the flow of methane in the macro-pores (fractures) of coal bed.

REFERENCES

Alpern, B., Lemos de Sousa, M.J. (2002) Documented international enquiry on solid sedimentary fossil fuels; coal: definitions, classifications, reserves resources, and energy potential. *Inter. J. of Caol Geology,* Vol. 50, pp. 3-41.

Andersen M.A. (2003), *Oilfield Review Schlumberger Autumn-2003*

Curl, S. J. (1978), Methane Prediction in coal mines, IEA coal Research, London, P50

Gamson P.D., Beamish B.B., Johnson D.P. (1992), Coal microstructure and micro permeability and their effects on natural gas recovery. Published In: *Fuel* Vol. 72, pp 186-193

Hargraves, A. J. (1984) particular gas problems of Australian deep coal mining. *Proceedings 3rd international mine ventilation congress, Harrogate* (U.K) Pp 127-133

Harpalani S., Schraufnagel R.A. (1990), Cleats and their relation to geologic lineaments and coal bed methane potential in Pennsylvanian coals in Indiana. Published In: International Journal of Coal *Geology*, Pp 124-132.

Harpalani S., Schraufnagel R.A. (1990), Shrinkage of coal matrix with release of gas and its impact on permeability of coal. *Journal Fuel*, Volume 69

Harpalani S., Zhao X. (1991). The effects of overburden stress on coalbed methane production. *Energy Sources*, Volume 13, Pp 204-217

Karacan, C. Ö., Esterhuizen, G. S., Schatzel, S. J. and Diamond, W. P. (2007). Reservoir simulation-based modeling for characterizing longwall methane emissions and gob gas venthole production. *International Journal of Coal Geology*, 71**,** 225-245.

Karacan, C. Ö., Ren, T. and Balusu, R. (2008). Advances in grid-based numerical modelling techniques for improving gas management in coal mines. *12th US/North American Mine Ventilation Symposium.* Sparks, Nevada, USA.

Karacan, C. Ö., Ruiz, F. A., Cotè, M. and Phipps, S. (2011). "Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction." *International Journal of Coal Geology,* 86**,** 121-156.

Lama, R. D., and Nguyen, V. U. A. (1987) A model for determination of methane flow Parameters in coal from desorption tests, *Proceeding of the 20th international symposium on the application of computers and mathematics in mineral industries. Volume 1: mining, Johanesburg,* Pp 275-282.

Mazumder S., Herment P.V., Bruining J., Wolf K.H.A.A. (2001), A preliminary model of CO_2 sequestration in coal for improved coalbed methane production. *The 2001 Alabama Coal bed Methane Symposium*

Saulsberry, J.L., Schafer, P.S., Schraufnagel, R.A. (1996). A Guide to Coal bed Methane Reservoir Engineering. Gas Research Institute, Chicago, U.S.A.

Wang, Z. (2013) Application of computational fluid dynamics modeling in underground coal mines; *PhD Thesis, School of civil, mining and environmental Engineering, University of Wollongong, Australia.*