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Numerical modeling of gas flow in coal pores for methane drainage

Adel Taheri [a, *], Farhang Sereshki [a], Faramarz Doulati Ardejani [b], Ali Mirzaghorbanali [c]

[a] School of Mining, Petroleum & Geophysics Engineering, Shahrood University of Technology, Shahrood, Iran
[b] School of Mining, College of Engineering, University of Tehran, Iran
[c] School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW, Australia

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ABSTRACT

The sudden explosion of methane during underground coal mining is a major dilemma. To mitigate its occurrence and reduce the extent of methane diffusion, gas drainage operations are carried out before mining. This paper investigates methane gas flow in a coal block in order to calculate the pressure of gas and its molecule velocity for methane gas drainage operation. A coal piece surrounded by cleats was used for geometrical modeling and numerical simulation. Movements of fluid and gas molecules in a porous medium were successfully simulated. The numerical solution is based on COMSOL Multiphysics software. The validity of the numerical simulation was assessed using an analytical model with satisfactory results.

1. Introduction

Coal bed methane is one of the major causes of underground coal mine explosions. Despite the negative financial and environmental impacts of coal bed gas, it is still considered as a fuel source (MacDonald, 1990). Coal gasification is a sequence of thermo-chemical transformations taking place at high temperature between the organic part of coal matter and gasifying agents, such as oxygen, steam, air and carbon dioxide (Cempa-Balewicz, Laczny, Smolinski, & Iwaszenko, 2013). Methane is present within the natural pores of coal and micro pores of coal matrix, some of this methane is absorbed by coal molecules and bonded to them (Holditch, 1989). Coal seam gas content increases with depth and mining intensity in underground coal mines, and is a primary factor in mining safety and efficiency. Coal is a complex porous medium that consists of primary pores and fissures that result from tectonic movement, therefore, it has a large amount of free space and multiple pore surfaces. Coal seam gas exists in an adsorbed and free state. Only free gas can flow to a working face or be extracted (Wang, Wu, & Zhang, 2015). The amount of free state methane depends on many factors. These include:

- The structure and permeability of the overburden strata,
- Methane desorption rate from the unexploited gassy coal seams, which are distressed as a consequence of earlier mining,
- The spatial location of these unexploited coal seams in relation to the water level in a flooded mine (Krause & Pokryszka, 2013).

If underground coal seams are pressurized, coal molecules will be trapped within the seams. If there is a pressure drop (due to mining, construction of a front or gas drainage drilling), coal molecules will start to move towards the low pressure area. As coal has high potential for absorbing methane, coal seams will accumulate a considerable amount of gas. For example, 450 gm of coal has an absorbing surface of 46,500 m^2 (Sereshki, Aziz, & Porter, 2003). Although coal is of a porous nature with low permeability, its pore structure is far more complex than ordinary layers of other rocks (Soeder, 1991). Natural fractures and coal permeability create a route for gas and water to flow into coal seams from the cleats. Cleats in a coal seam are natural systematic fractures similar to those of sedimentary rocks (Kendall & Briggs, 1993). Cleat systems are among the features of gas reservoirs that influence the economic viability of gas drainage from coal seams. This affects the success or failure of such projects, and is influential in the progress of gas drainage operations (Dhir, Dern, & Mavor, 1991). Cleats are considered an indicator of permeability in coal that follows Darcy's law for water and gas. There are two sets of cleats, face and butt cleats which are orthogonal to each other (Gray, 1987). Face cleats usually have planar and smooth fractures and form the main part of the fracture system. The permeability of coal bed methane is 3–10 times greater in the direction of the face cleat, when compared to other directions (Mcculloch, Duel, & Jeran). In coal seams, there is a two-phase flow of gas into the well bore. In the first phase, the

* Corresponding author.
E-mail address: Adel_Taheri@Shahroodut.ac.ir (A. Taheri).

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absorbed methane diffuses through the micro pores of the coal matrix and reaches the natural fracture (cleats). In the second phase, the gas flow passes through the face and butt cleats and reaches the well bore, depending on the pressure differentials as described by Darcy law (Harpalani & Schraufnagel, 1990). The flow of methane is a function of effective coal permeability. According to mathematical and computerized models of methane drainage, the distance between micro pores and cleats plays an important role in methane gas flow in coal seams (Harpalani, Zhao, & Farmer, 1992). In an undisturbed coal seam, however, methane molecules remain in the micro pores of the coal matrix (Solano, Mastalerza, & Schimmelmann, 2007).

In this study, a two dimensional coal matrix model surrounded by rectangular blocks, is developed for gas drainage through two face and butt cleats. It is assumed that there are only six pores in each coal matrix block. The methane that diffuses through the micro pores and cleats will eventually reach the main fractures. These joints allow diffused methane to enter the wellbore. The COMSOL Multiphysics software was incorporated to simulate this phenomenon, which is the subject of the paper.

2. Materials and methods

A simulation of the process of gas flow from micro pores inside coal towards cleats was developed. In this simulation, the method of mass and energy transfer was applied. Firstly, general equations for mass transfer in a porous space were defined. Subsequently, the method of Probability Density Function (PDF) was adopted for the process of methane gas diffusion in coal (Society of Composite energy, 2014). This method is based on solving the equation for the movement of a mixture in a closed medium where the combination of mass and energy remains constant (Janoszek, Laczny, Stanczyk, Smolinski, & Wiatowski, 2013). Other assumptions applied in model development include:

1. Methane gas flow inside the cleats is laminar and follows Darcy's law,
2. Temperature remains constant in the coal environment during the gas extraction process,
3. Cleats are straight and without any twists,
4. There are no coal particles in these cleats,
5. No matrix shrinkage occurs due to methane drainage,
6. Permeability is postulated to follow Klinkenberg's law,

The continuity function for the gas phase of a fluid is extended as (Table 1 defines parameters used in these equations):

$$-\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[\frac{rP_a}{Z_{Pa}}\overrightarrow{v}\right]+\frac{RT}{M}\frac{q_m}{V_{ba}}+\frac{RT}{M}\frac{q_{ai}}{V_{ba}}=\varnothing_a\frac{\partial}{\partial t}\left[\frac{P_a}{Z_{pa}}\right] \quad (1)$$

According to Darcy's law, the equation for the flow in a fracture is defined as:

$$\overrightarrow{v}=-\left[\frac{k}{\mu}\right]\left(\frac{\partial P_a}{\partial r}\right) \quad (2)$$

By substituting Equation (2) in Equation (1):

$$\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[\frac{krP_a}{Z_{Pa}\mu}\left(\frac{\partial P_a}{\partial r}\right)\right]+\frac{TP_{SC}}{T_{SC}}\frac{q_{SC}}{V_{ba}}+\frac{RT}{M}\frac{q_{ai}}{V_{ba}}=\varnothing_a\frac{\partial}{\partial t}\left[\frac{P_a}{Z_{pa}}\right] \quad (3)$$

According to Fick's law of diffusion, the flow in pores is obtained using:

$$\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[rD\left(\frac{\partial C}{\partial r}\right)\right]=\left(\frac{\partial C}{\partial t}\right) \quad (4)$$

Values of gas absorption and drainage are determined from Langmuir's equation:

$$V_E=\frac{V_\infty P}{P+P_L} \quad (5)$$

The total concentration of the gas in a coal matrix per unit of volume is obtained using the following relationship:

$$C=\left(\frac{PM\varnothing_i}{ZRT}\right)+\left[\frac{V_\infty P}{P+P_L}\right] \quad (6)$$

By introducing the value of C from Equation (4), the following governing equation for numerical simulation is obtained (Janoszek et al., 2013):

$$\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[rD\left(\frac{\partial}{\partial r}\left\{\left(\frac{PM\varnothing_i}{Z_pRT}\right)+\left[\frac{V_\infty P}{P+P_L}\right]\right\}\right)\right]=\frac{\partial}{\partial t}\left[\left(\frac{PM\varnothing_i}{Z_pRT}\right)+\left[\frac{V_\infty P}{P+P_l}\right]\right] \quad (7)$$

3. Results and discussion

As with every numerical simulation, the model characteristics including interface thickness, mesh size and diffusion coefficient were determined (Akhlaghi Amir, & Hamouda, 2013). For this purpose, the pores in which the gas diffuses were plotted in the coal block. It was assumed that there were six gas pores in each 100 × 200 mm coal block. The geometry and other relevant required data were introduced to the software as shown in Fig. 1.

Pores containing methane gas and the rectangular coal blocks have the characteristics as shown in Fig. 2. Also, the material parameters used in the numerical simulation are listed in Table 2.

The Finite Element method with interfacial adaptive mesh refinement was employed to solve the governing equation (Akhlaghi Amir, & Hamouda, 2014). Since the software is based on

Table 1
Relevant parameters used for model development.

Symbol	Description	Symbol	Description
C	Gas concentration in coal matrix (kg/m^3)	t	Time (s)
D	Diffusion coefficient (cm^2/sec)	T	Temperature (K)
K	Permeability md	V_E	Equilibrium isotherm (kg/m^3)
M	Molecular weight (kg/kmol^3)	V_∞	Langmuir volume constant (kg/m^3)
P	Pressure psi (kPa)	Z	Gas compressibility factor
P_L	Langmuir pressure constant (psi, kPa)	M	Viscosity cp
Q	Volumetric flow rate(std m^3/s)	P	Density (kg/m^3)
q_m	Mass flow rate (kg/s)	Φ	Porosity
R	Universal gas constant		

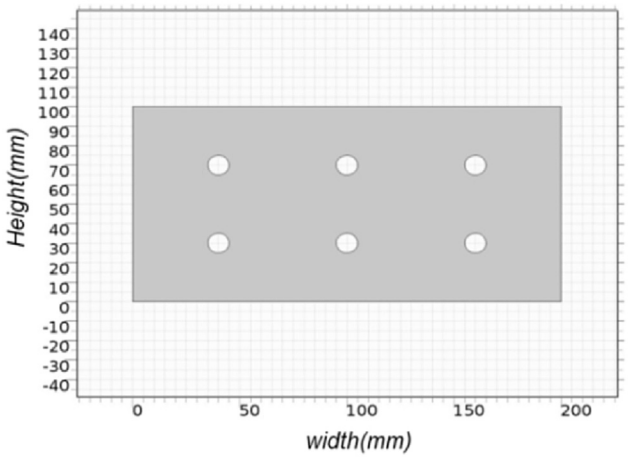

Fig. 1. The model geometry and input parameters applied for numerical simulation.

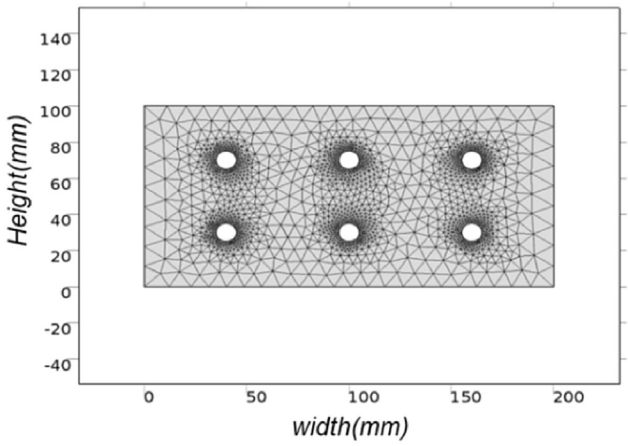

Fig. 3. Finite element mesh for numerical simulation.

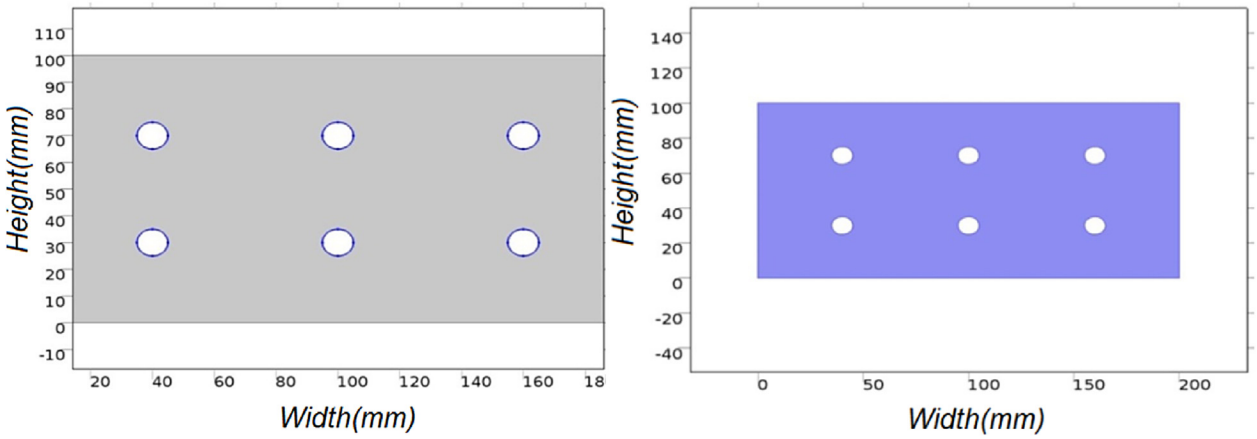

Fig. 2. Material characteristics used for numerical simulation.

Table 2
Material parameters used for model.

Name	Value	Unit
Permeability	3.75×10^{-11}	m^2
Porosity	0.03	–
Density	1370	kg/m^3
Dynamic viscosity	10^{-4}	$Pa \times s$

Table 3
Mesh properties used for model.

Property	Value	Name	Value
Minimum element quality	0.6318	Maximum element size	13.4
Average element quality	0.8924	Minimum element size	0.06
Triangular elements	3506	Curvature factor	0.3
Edge elements	206	Maximum element growth rate	1.3
Vertex elements	28		

the Finite Element Method (FEM), the meshing process was conducted as shown in Fig. 3 and Table 3.

After implementing the model and solving any problems, the software produced the results as given in Fig. 4. The output of the model contains diagrams of velocity and pressure in various parts.

It is inferred from Fig. 4 that the velocity of gas in cleats is 0.0007 m/s while the speed of gas emission in pores is 0.002 m/s. It is noted that the gas pressure in joints decreased by about 20–25 times from emission. In addition, there is a maximum gas pressure in the internal space of the coal block where outburst may happen if gas drainage is not carried out prior to mining. The model specifies gas molecules and suggests the minimum distance for gas molecules to reach joints and free spaces. This indicates that hydraulic fracturing may become necessary in order to drain gas properly before mining commences.

3.1. Model validation

In this paper, diagrams of velocity and pressure are plotted for a pore and also a joint located in the border of a coal block (Fig. 5), where there is reasonable agreement between the velocity and pressure graphs. For model validation, the analytical model developed by the American Society of Composite Energy (2014) was incorporated to validate the numerical simulation. Fig. 6 shows the movement of gas molecules within the joint as calculated by the analytical model. The average speed of the gas molecules was calculated as 0.005 m/s (Society of Composite Energy, 2014). This figure is in line with the results of the numerical simulation. It is noted that the proposed analytical model used in this study for model verification possesses limited capabilities in simulating complex geological structures such as those encountered in coal mines. However, considering the fact that the aforesaid analytical

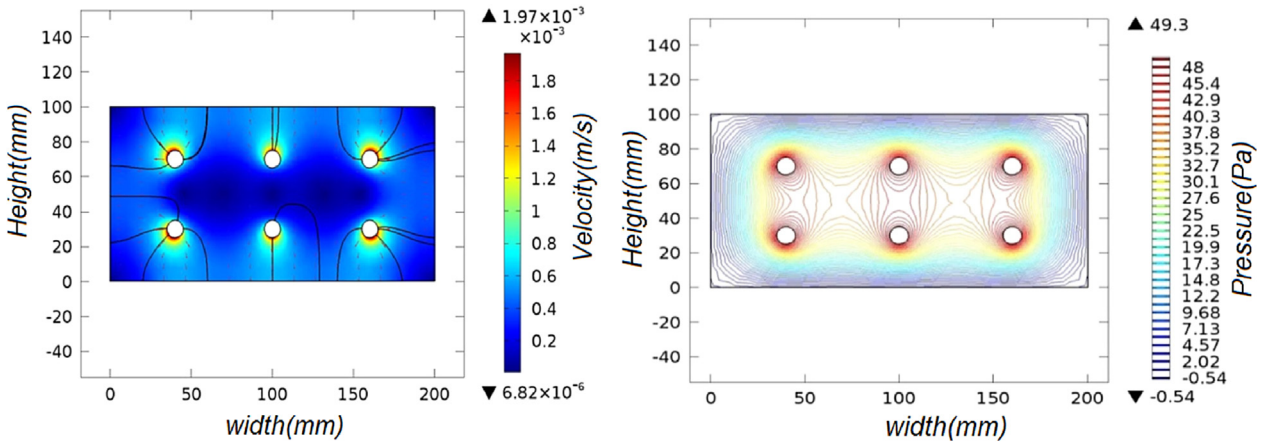

Fig. 4. Plots of velocity and pressure.

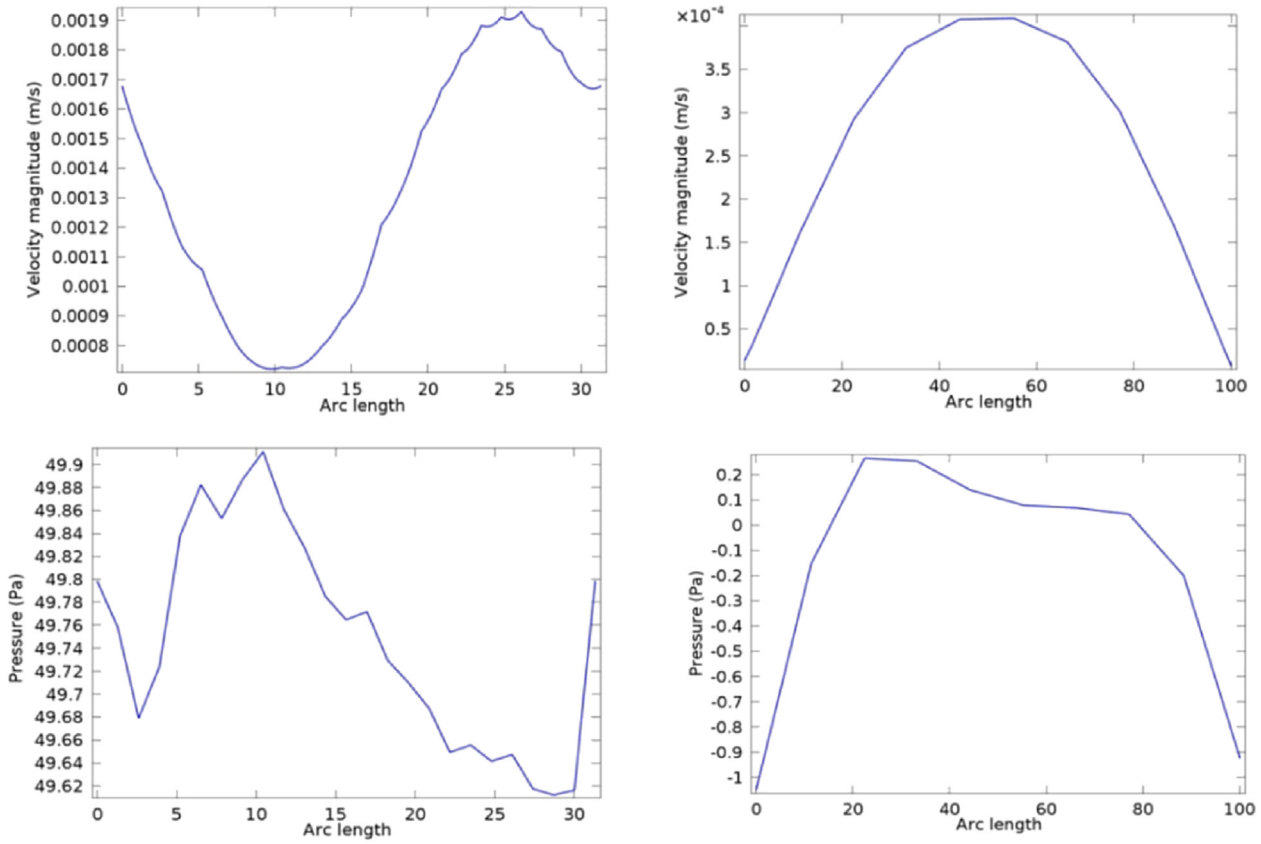

Fig. 5. Velocity and pressure diagrams for a specific pore and joint.

model is based on proven physical and mathematical concepts, it still can be applied to evaluate the results of numerical simulations.

4. Conclusions and recommendations

A complex numerical model for gas drainage operations was developed in this study. The following main conclusions were drawn from this investigation:

- The velocity of coal bed methane in a coal sample is around 0.0007 m/s for the given input parameters. This figure varies based on the porosity of coal and the number of joints,
- Gas velocity is inversely proportional with the possibility of immediate gas emission,
- The amount of output pressure of coal bed methane in a coal sample indicates that if a coal pore's pressure is 345 kPa (regardless of air pressure), the pressure will drop to 13.8 kPa at the time of gas emissions in joints with the given input parameters.

This study can be extended to consider the following aspects that were not studied as part of this investigation:

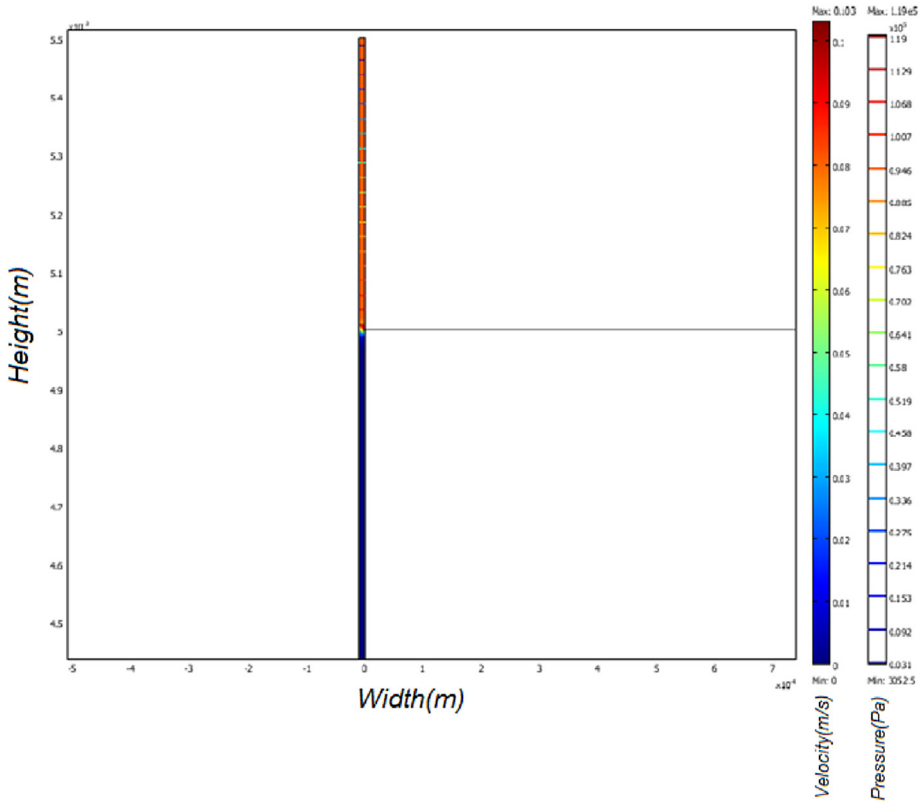

Fig. 6. Velocity field surface map and pressure contours for a cleat based on the analytical model.

- Input parameters may affect the results of a numerical simulation. In this study, input parameters were selected to suit the Tabas coal mine in Eastern Iran. It is recommended that a comprehensive sensitivity analysis on input parameters such as permeability, porosity, density and dynamic velocity to evaluate their effects on results of numerical simulation be carried out,
- Extension of this study to further assess the capabilities of the proposed numerical model against collected experimental data. Currently, this is being carried out at the School of Mines, Shahrood University of Technology and will be released upon completion of the study.

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References

Akhlaghi Amiri, H. A., & Hamouda, A. A. (2013). Evaluation of level set and phase field methods in modeling two phase flow with viscosity contrast through dual-permeability porous medium. *International Journal of Multiphase Flow, 52*, 22–34.

Akhlaghi Amiri, H. A., & Hamouda, A. A. (2014). Pore-scale modeling of non-isothermal two phase flow in 2D porous Media: Influences of viscosity, capillarity, wettability and heterogeneity. *International Journal of Multiphase Flow, 61*, 14–27.

Cempa-Balewicz, M., Laczny, M., Smolinski, A., & Iwaszenko, S. (2013). Equilibrium model of steam gasification of coal. *Journal of Sustainable Mining, 12*(2), 21–28.

Dhir, R., Dern, R. R., & Mavor, M. J. (1991). *Economic and reserve evaluation of coal bed methane reservoirs*. Texas, USA: Society of petroleum engineers, Paper No. 22024.

Gray, I. (1987). *The physical process of gas storage in movement in coal seams*. Society of Petroleum Engineers & Reservoir Engineers.

Harpalani, S., & Schraufnagel, R. A. (1990). Shrinkage of coal matrix with release of gas and its impact on permeability of coal. *Journal of Fuel, 69*, 551–556.

Harpalani, S., Zhao, X., & Farmer, I. W. (1992). .Mechanics of gas flow in coal - A laboratory investigation. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics, 29*(2), A94.

Holditch, S. A. (1989). Enhanced recovery of coal bed methane through hydraulic fracturing. In *SPE annual technical conference and exhibition*. Houston, Texas: Pub: Society of Petroleum Engineers.

Janoszek, T., Laczny, M. J., Stanczyk, K., Smolinski, A., & Wiatowski, M. (2013). Modeling of gas flow in the underground coal gasification process and its interactions with the rock environment. *Journal of Sustainable Mining, 12*(2), 8–20.

Kendall, P. F., & Briggs, H. (1993). The formation of rock joints and the cleats of coal. *Royal Society of Edinburgh, 53*, 164–187.

Krause, E., & Pokryszka, Z. (2013). Investigations on methane of closed coal mines. *Journal of Sustainable Mining, 12*(2), 40–45.

MacDonald, G. J. (1990). *The future of methane as an energy resource* (Vol. 15). Annual Review of Energy. Virginia, USA.

Mcculloch C. M., Duel M., Jeran P. W., Cleats in Bituminous Coal Bed, Reports of Investigations No. 7910, US Bureau of Mines.

Sereshki, F., Aziz, N., & Porter, I. (2003). Impact of coal permeability on gas sorption and coal volume change. In *Proceedings of the 7th annual environmental engineering research event conference, Marysville, Victoria, Australia* (pp. 333–342).

Society of Composite Energy. (2014). *Mathematical modeling of methane flow in coal matrix using COMSOL*. Retrieved June 4, 2016, from http://www.ems.psu.edu/~elsworth/courses/EGEE520/2009Deliverables/reports/Hemant__Spring09_EGEE_520_Modelling_Methane.pdf.

Soeder, D. J. (1991). *The effects of overburden stress on coal bed methane production*. Tec book, Geology in Coal Resources Utilization.

Solano, W. A., Mastalerza, M., & Schimmelmann, A. (2007). Cleats and their relation to geologic lineaments and coal bed methane potential in Pennsylvanian coals in Indiana. *International Journal of Coal Geology, 72*, 187–208.

Wang, J., Wu, R., & Zhang, P. (2015). Characteristics and applications of gas desorption with excavation disturbances in coal mining. *International Journal of Coal Science & Technology, 2*, 30–37.