Numerical Simulation of Integrated Reservoir-Borehole Flow for Pre-Mining Drainage

Mohsen Azadi  
*University of Queensland*

Saiied Mostafa Aminossadati  
*University of Queensland*

Zhongwei Chen  
*University of Queensland*

Follow this and additional works at: https://ro.uow.edu.au/coal

Recommended Citation  
Mohsen Azadi, Saiied Mostafa Aminossadati, and Zhongwei Chen, Numerical Simulation of Integrated Reservoir-Borehole Flow for Pre-Mining Drainage, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2016 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019  
https://ro.uow.edu.au/coal/613

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
NUMERICAL SIMULATION OF INTEGRATED RESERVOIR-BOREHOLE FLOW FOR PRE-MINING DRAINAGE

Mohsen Azadi, Saiied Mostafa Aminossadati and Zhongwei Chen

ABSTRACT: The accumulation of methane in coal seams and surrounding geological structures as well as underground coal mines has been the major contribution to gas outbursts and mine explosions. Drainage of Coal Seam Gas (CSG) prior to mining using Surface to In-seam (SIS) and Underground In-seam (UIS) boreholes is crucial to reducing the potential risk to the safety and productivity of underground mining operations. Many researches have been carried out to identify the factors affecting the gas drainage performance such as coal properties, gas content and drainage borehole geometries. Two different flow conditions determine the gas drainage efficiency: borehole flow with injection from wall and reservoir flow in a porous medium. These two different types of flow have previously been studied separately. However simultaneous flow of gas through reservoir and borehole requires further investigation.

In this research, a three dimensional model for simulation of integrated reservoir-borehole flow is developed to study the significant effect of borehole geometry on flow characteristics of coal seams. Computational Fluid Dynamics (CFD) simulations were carried out using finite volume based software ANSYS Fluent. Four different borehole diameters of 7.5, 10, 12.5 and 15 cm as well as three different lengths of 50, 100, and 150 m were chosen to accomplish the parametric study of borehole geometry. It is assumed that the boreholes are in a steady state condition for two different single phase scenarios of liquid flow (water) and gas flow (methane). The CFD simulations are validated with previous pressure drop models for internal single phase gas and liquid flow. The obtained results reveal that increasing the borehole diameter leads to reduction in fluid pressure throughout the coal seam. On the effect of borehole length it is seen that at a specific distance from borehole outlet, the pressure distribution is independent of the borehole length and upstream effects.

INTRODUCTION

Many engineering and industrial applications still rely on coal as a major energy source. Coal seam reserves contain a considerable amount of gas. In a general estimation, the gas content for different types of coal varies between 0.1 to 25 cubic meter of gas per ton of coal. Coal seam gas (CSG) is mainly composed of methane which is estimated at 80%-95% of overall gas content. Methane gas is removed prior to mining to ensure the safety of mining workings. The challenges involved in coal extraction are growing remarkably as underground mines are becoming deeper, gassier and more complicated in geometry.

Mining pre-drainage is the most important prerequisite for removing methane gas from deep and gassy coal reservoirs to achieve a safe environment for mining exploitation operations. In addition to mining concerns, this process leads to gas production as another valuable source of energy. In spite of significant progress in the development of underground mining technologies and improvement of mine safety, there are still fatal accidents and explosions happening in underground coal mines.

One of the major concerns related to mining pre-drainage is gas ventilation control and management. Two major method are used to satisfy the required safety standards in terms of reservoir gas content: i) Surface to In-seam (SIS); and ii) Underground In-seam (UIS) drilling of boreholes for water and gas drainage. To develop these boreholes, drilling is conducted directionally from vertical to horizontal sections with different diameter ranges for the purpose of gas content reduction from the coal.
A reliable prediction of coalbed methane flow depends on the different mechanisms concerned with coal structure and reservoir properties as well as drainage borehole geometry. Accordingly, many studies have been performed focusing on either reservoir simulations or borehole flow and pressure drop predictions. However, most of these investigations are basically designed for oil and gas applications with more focus on reservoir engineering aspects. In comparison, less attention has been paid to CSG flow studies with specific focus on borehole impacts on simultaneous flow of gas through coal seam and boreholes.

Many studies have been carried out to simulate flow of fluids from different types of reservoirs into wells or boreholes (Jenkins and Aronofsky, 1953; Aronofsky and Jenkins, 1954; Al-Hussainy et al., 1966; Yao et al., 2013). Early theoretical models or numerical simulations were designed for oil and gas applications. Jenkins and Aronofsky (1953) presented a numerical method for describing the transient flow of gases in a radial direction for a porous medium for which the initial and terminal pressure and/or rate are specified. They developed a simple means for predicting the well pressure at any time in the history of a reservoir. In their next study (Aronofsky and Jenkins 1954) suggested an effective drainage radius was for which steady state gas flow assumption could be used to predict well pressure in the process of gas reservoir depletion. In a rigorous model Al-Hussainy et al., (1966), considered the effect of variations of pressure dependent viscosity and gas law deviation factor on the flow of real gases through porous media. They used pseudo-pressure as change of variable to reduce the equations to a form similar to diffusivity equations. Yi et al., (2009) simulated gas flow through a reservoir using two dimensional solid-gas coupled software RPFA to study the effect of permeability, borehole spacing and diameter and gas content on reservoir pressure and drainage radius. Packman et al., (2011) used SimedWin to simulate CSG flow in an attempt to demonstrate the ability of enhanced gas recovery to increase gas flow rate. Based on their reservoir model calibrated by history matching, they concluded that with regard to increased gas flow rate and decreased drainage time, enhanced gas recovery through injection of nitrogen is achievable. Most of these researches have focused only on reservoir aspects of simulation and their assumptions need further investigations in terms of flow dimensions. The errors concerned with simplifying assumptions limit the range of application of these reservoir simulators. Moreover, borehole flow is defined as a boundary condition and is not included in the mathematical modelling and governing equations of the reservoir simulators. These assumptions neglect the interactions at reservoir and borehole interface and need further attention.

On the effect of borehole wall influx or outflux, a number of studies have been carried out to understand the flow filed behaviour and pressured drop along boreholes (Asheim et al., 1992; Yuan 1997; Su and Gudmundsson 1998; Yuan et al., 1999). Siwon (1987) developed a one-dimensional model for steady state flow of incompressible fluid in a horizontal pipe perforated with circular orifices. Ouyang et al., (1998) continued this study by developing a pressure drop model for pipes with perforated wall that can easily be used in reservoir simulators or analytical models. This model considers different types of pressure drops including: frictional, accelerational, gravitational as well as pressure drop caused by inflow. They concluded that for laminar flow, wall friction increases due to inflow whereas for turbulent flow wall friction decreases as a result of inflow.

Based on this approach, more attempts have been carried out to obtain the most accurate pressure drop models for borehole flow. Yalniz and Ozkan (2001) investigated the effect of inflow from horizontal wall on flow characteristics and pressured drop experimentally and theoretically. They developed a generalized friction factor correlation that is a function of Reynolds number, the ratios of inflow to wellbore flow rate and perforations to wellbore diameter. Wang et al., (2011) measured pressure drop due to inflow in a horizontal perforated pipe loop by using water as working fluid. Their experimental results show that pressure drop grows as a result of increased injection flow rate. They developed a model that suggests that total pressure drop consists of two parts including perforated pipe wall friction loss and an additional pressure drop term. In a recent study, Zhang et al., (2014) presented a comprehensive model for prediction of pressure drop based on the previous studies and some new experiments. Their results show that this model presents more accurate results compared to previous models and can also be used for a wider application range. It must be noted that none of the these
studies has been conducted to develop a model for prediction of pressure drop and production rate for coal seam boreholes with inflow and most models developed so far are derived for oil and gas flow conditions.

In addition to theoretical models, some researchers have simulated borehole flow using numerical techniques to avoid the simplifying assumption (Folefac et al., 1991; Seines et al., 1993; Siu et al., 1995; Su and Lee 1995; Yuan et al., 1998; Ouyang and Huang 2005). Guo et al., (2006) developed a numerical model to study the deliverability of multilateral wells. Their model was capable of coupling the inflow performance of the individual laterals with hydraulics in curved and vertical well sections. Zeboudj and Bahi (2010) simulated wellbore flow with pipe injection using Computational Fluid Dynamics (CFD) simulation as a replacement for further experiments. They discussed the experimental measurement shortcoming in the assumption of a constant momentum-correction factor which is not true in the case of wall inflow. CFD simulation, however, allows the exact calculation of this parameter by considering all variations of velocity in radial direction eliminating the need for making flawed assumptions. In another study, Ouyang et al., (2009) studied single-point wall entry for oil and gas wellbores. The significant effect of borehole hydraulics on production predictions, performance evaluations and completion design for horizontal and multilateral boreholes needs to be well understood. In this respect, they used CFD modelling using ANSYS to investigate flow profiles and pressure distribution along the wellbore thoroughly. Their simulation results showed that moving the entry point closer to the outlet section reduces the significant impact of inflow on the total pressure drop along the borehole. The simplifying assumption of constant and pre-defined wall inflow rate needs to be improved and evaluated further.

Depending on borehole geometry the flow characteristics through the coal seam and borehole may vary. Some theoretical models and reservoir simulators have been presented accordingly. However, most of them are either inaccurate due to simplifying assumptions or designed mainly for oil and gas or shale gas reservoirs. This is why operational experience, which is basically subjective, is still considered as an essential requirement for efficient gas drainage of coal seams. Efficient drainage of coal seams prior to mining requires a good understanding of reservoir and borehole conditions and their interactions. In this study, a large scale three dimensional model is developed using CFD simulations to study the integrated reservoir-borehole flow during coal seam drainage. The significant influence of borehole diameter and length on the coal seam flow behaviour is investigated.

MATHEMATICAL MODELLING

Model assumptions

Coal seams are generated by compression of plant and animal matter over millions of years. During this process CSG is trapped inside the coal seam by water and ground pressure. The methane gas is lied inside the coal matrix sealed with water existing in coal I fractures which are called cleats. As the reservoir pressure at wellbore falls the water begins to move out of cleats letting the gas be desorbed from the coal matrix. Based on the described drainage process, the following assumptions have been taken into consideration:

- Water was considered as working fluid for single phase liquid flow
- Methane as a compressible ideal gas was considered as working fluid for single phase gas flow
- The simulations are conducted in the single phase production phase in steady state condition
- Two cell zone conditions for porous coal seam and internal borehole flow were considered
- Coal is considered as a homogenous porous media holding gas in the coal matrix
- Fluid flow through the fracture network of coal obeys Darcy’s law
- No borehole boundary condition was defined at the borehole wall
- The flow variables are transferred between borehole and porous zone by defining an interface at the contact region of the two zones
- Flow through the borehole is considered turbulent
- Flow through the coal seam is considered laminar
One of the most determining parameters affecting drainage of coal seam is reservoir permeability. Depending on coal seam depth, the reservoir can be classified into three groups of shallow, medium-depth and deep. Coal permeability varies from near 0.1 to 100 $\text{md}$ for deep and shallow reservoirs, respectively (Darling 2011). In this study horizontal and vertical permeabilities of 10 $\text{md}$ and 1 $\text{md}$ were considered for coal seam zone, respectively.

**Governing equations**

Based on the mentioned assumptions two different sets of equations are required to simulate flow through the borehole and coal seam. Flow in the borehole section is considered internal turbulent pipe flow with distributed mass transfer through then wall and flow through coal seam is treated as a porous media.

**Borehole flow equations**

Considering varying mass transfer through borehole wall resulted from reservoir drainage the conservation equations of mass momentum and energy can be written as follows:

$$\frac{\partial}{\partial x_j}(\rho u_i) = 0$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j}\left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial \tau_{ij}}{\partial x_j} + \rho \ddot{g}$$

$$\nabla \cdot (\dot{v}(\rho E + P)) = \nabla \cdot (k_{eff} \nabla T + (\tau_{ij} \cdot \dot{v}))$$

Where:

$$\tau_{ij} = -\rho u_i u_j$$

$$E = h - \frac{P}{\rho} + \frac{v^2}{2}$$

In the above equations, $\tau_{ij}$ is the Reynolds stress tensor which represents the effect of turbulent fluctuations on fluid flow. This term was computed using standard $k-\varepsilon$ turbulence models to close the mass and momentum equations. For the Energy equation, $k_{eff}$ is the effective conductivity which is equal to $k + k_t$, where $k_t$ is the turbulent thermal conductivity, defined according to the turbulence model being used. The second term on the right-hand side of Eq. (3) represents energy transfer due viscous dissipation. The details of turbulence models used in the current study with all the constant values can be found in FLUENT theory guide (2011).

**Reservoir flow equations**

Since the volume blockage that is physically present is not represented in the model, a superficial velocity inside the porous medium was used, based on the volumetric flow rate, to ensure continuity of the velocity vectors across the porous medium interface. The porous media is modelled by the addition of a momentum sink term to the standard fluid flow equations. To do this, Darcy flow is considered through the coal fracture network. Under the suggested assumptions for coal seam zone, the conservation equations are written below:

$$\frac{\partial}{\partial x_j}(\rho u_i) = S_m$$
\[
\frac{\partial}{\partial x_j} (\rho u_j) = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_i}{\partial x_i} \right) + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g + \bar{S}_j \right] \tag{7}
\]

where \(S_m\) is the mass source term accounting for the desorption of gas from coal matrix and:

\[
\bar{S}_j = -\frac{\mu}{k} \bar{v}_j 
\tag{8}
\]

This momentum sink contributes to the pressure gradient in the porous cell, creating a pressure drop that is proportional to the fluid velocity in the cell.

ANSYS FLUENT solves the standard energy transport equation (Eq. 3) in porous media regions with modifications to the conduction flux. For simulations in which the porous medium and fluid flow are assumed to be in thermal equilibrium, the conduction flux in the porous medium uses an effective conductivity:

\[
\nabla \cdot \left( \bar{v} (\rho E + P) \right) = S^h_f + \nabla \cdot \left( k_{\text{eff}} \nabla T + \left( \tau_{\text{eff}} \cdot \bar{v} \right) \right) \tag{9}
\]

where \(\rho\) is fluid density, \(\rho_s\) is solid medium density, \(\varphi\) is porosity of medium, \(k_{\text{eff}}\) is effective thermal conductivity of medium and \(S^h_f\) is fluid enthalpy source term.

**Computational model**

A UIS borehole drilled through a section of coal seam is chosen as the base physical model. A 100 \times 5 m coal panel with seam thickness of 2.5 m and a borehole of 10 cm in diameter was considered as the baseline condition. User defined mass source term compiled in C language were implemented in Fluent solver to account for desorption of fluid from the porous coal seam zone. Outlet atmospheric pressure boundary condition at the borehole end was assumed. Four different borehole diameters of 7.5, 10, 12.5 And 15 cm as well as three different lengths of 50, 100, and 150 m were chosen to accomplish the parametric study of borehole geometry. The coal seam-borehole models generated for the current simulations are presented in Figure 1.

The Semi-implicit Method Pressure-linked Equations (SIMPLE) algorithm was used for the pressure–velocity coupling. The second-order upwind discretization scheme was utilized for momentum, turbulent kinetic energy, and turbulent dissipation rate. The computations were carried out using parallel processing on a high performance computing workstation with 12 nodes. Each node is configured as follows: 2 \times 10 cores @2.60GHz, 128GB RAM.
RESULTS AND DISCUSSION

Validation of the model

From the baseline condition, the borehole diameter and length were varied to accomplish a valid parametric study of integrated coal seam-borehole flow. All the simulations were run for both methane flow and water flow as the working fluids during pre-mining drainage of underground coal seams.

The computed results for methane flow through borehole were compared with Atkinson's equation (Le Roux 1990) to give the pressure drop using the following equation:

$$\Delta P = \frac{kP_{er}L}{A^3} \frac{\rho}{\rho_{air}} Q^2$$

where $\Delta P$ is the pressure drop (Pa), $k$ is Atkinson friction factor (kg/m$^3$), $P_{er}$ is borehole perimeter (m), $A$ is cross-sectional area (m$^2$), $\rho$ is gas density (kg/m$^3$), and $Q$ is gas flow rate (m$^3$/s). The computed pressure drops for four different diameters (coloured with diameters) as well as three different lengths at $x=50$ m for borehole diameter of 10 cm are presented in Figure 2. The simulation results show good agreement with Atkinson’s equation. For water flow, the model results were compared with the following pressure drop model along pipes (Aziz and Govier 1972):

$$P_{air}$$

$$\Delta = \frac{kP_{er}L}{A^3} \frac{\rho}{\rho_{air}} Q^2$$

Figure 1: Coal seam-borehole models with different borehole diameters and lengths

Figure 2: Comparison of simulated model for methane flow with Atkinson equation (Le Roux 1990)
Development of a three dimensional and integrated model through coal seams can be used as a promising tool to improve our understandings about flow field variables and behaviour. The velocity streamlines through coal seam and borehole are illustrated in Figure 4. As presented in this figure, fluid flow originates from coal matrix and is injected to boreholes due to near borehole effects and negative pressure gradient. These results are essential for advancement of borehole development plans and efficient drainage methods where few in situ data are available due to access limitations and geometrical difficulties. Another advantage of the current model is providing flow field data at any point through the coal seam for any given geometry and operating condition using a fast and cost effective computer model.

**Effect of borehole diameter**

Pressure contours at five planes ($x=0, 25, 50, 75, 100$ m) along and three planes ($z=0, 2.5, 5$ m) across the coal seam for single phase gas and water flow are illustrated in Figure 5. The obtained results show that by increasing the borehole diameter the fluid pressure throughout coal seam falls resulting in more efficient drainage of the coal seam. This behaviour can be explained by bigger drainage area and
smaller pressure drop along the boreholes and proves the significant influence of borehole flow on pressure distribution through reservoir.

Figure 4: Velocity streamlines through coal seam reservoir and borehole

(a)

(b)
To scrutinise the effect of borehole diameter on coal seam pressure distribution closely, the pressure profiles in horizontal and vertical direction across coal seam were plotted at $x=50$ m (Figures 6-7). As expected, moving from borehole to coal seam in both horizontal and vertical direction, the pressure grows sharply until reaching nearly a constant value far from borehole. A close comparison of pressure distributions for methane and water flow reveals that pressure variations under the effect of borehole diameter are more significant for water flow than methane flow.

Figure 5: Pressure contours along coal seam for different borehole diameters for: a) methane flow, and b) water flow

Figure 6: Pressure distribution in Z direction across coal seam at $x=50$ m for: a) methane flow, and b) water flow
Figure 7: Pressure distribution in Y direction across coal seam at x=50 m for: a) methane flow, and b) water flow

Velocity profiles for four different borehole diameters along the borehole centreline for methane and water flow are presented in Figure 8. As expected, the velocity magnitude varies inversely with borehole diameter to satisfy the continuity of mass flow rate at the borehole outlet for similar fluid production from the coal seam. Velocity profile along a vertical direction at three different sections along borehole (x=1, 50, 100 m) for methane and water flow are presented in Figure 9. It is observed that velocity magnitudes across boreholes are remarkably larger than through porous coal seam. It can also be seen that moving from coal seam end to outlet section, the velocity magnitude increases considerably due to continuous injection of fluid along the borehole.

Figure 8: velocity along borehole centreline for: a) methane flow, and b) water flow

Effect of borehole length

Pressure contours for different borehole lengths at three planes with similar distance from borehole outlet (L-x=0, 25, 50 m) and three planes (z=0, 2.5, 5 m) across the coal seam for single phase water flow are presented in Figure 10. These three planes along the borehole were chosen to investigate the influence of upstream effects on drainage behaviour and pressure distribution through coal seams with longer boreholes. Pressure through the coal seam in the far from borehole regions does not vary significantly along the coal seam in the x direction. This behaviour can be explained by the greater value of coal permeability in the horizontal plane compared with the vertical plane. The computed
results indicate that for a specific distance from the borehole outlet, the pressure distribution is almost independent of borehole length and upstream effects. This behaviour is investigated further by plotting pressure profiles across the horizontal and vertical directions through coals seams of different lengths \((x=50,100,150 \text{ m})\) as presented in Figure 11. As can be seen, the curves overlap which confirms the previous interpretations.

Figure 9: Velocity profile along Y direction for methane (left) and water (right) flow at: a,c) \(x=1 \text{ m}\); b,d) \(x=50 \text{ m}\); e,f) \(x=100 \text{ m}\)
Velocity profiles across the vertical direction at a distance of 25 m from the borehole outlet for three different coal seam lengths $x=50, 100, 150$ m, are presented in Figure 12. As one can be seen, the longest coal seam has the highest velocity magnitude across the borehole which can be explained by higher injection from upstream to borehole for longer coal seam case. Same findings presented for Figures 10-12, were observed for the effect of borehole length on single phase methane flow through coal seam and borehole.
CONCLUSIONS

A three dimensional CFD model for simulation of integrated reservoir-borehole flow is developed to study the significant effect of borehole geometry on flow characteristics of coal seams. Four different borehole diameters and three lengths were simulated for single phase methane and water flow. Using computer simulations, it was shown that by increasing the borehole diameter, the fluid pressure throughout the coal seam falls resulting in more efficient drainage of the coal seam. It can also be seen that velocity magnitude is remarkably large across borehole than through porous coal seam and moving from coal seam end to outlet section, the velocity magnitude increases considerably due to continuous injection of fluid along the borehole. A close comparison of pressure distributions for methane and water flow reveals that pressure variations under the effect of borehole diameter are more significant for water flow than methane flow. Pressure through the coal seam in the far from borehole regions does not vary significantly along the coal seam in the x direction. In addition, the computed results indicate that for a specific distance from the borehole outlet, the pressure distribution is almost independent of borehole length and upstream effects. This study proves that the presented CFD model can be used as a promising tool for pre-mining drainage simulations. This model can provide the mining industry with in situ data using inexpensive, flexible and fast computer simulation.

REFERENCES

Darling, P, 2011. SME Mining Engineering Handbook. Littleton, SME.


