An innovative model for coal seam gas release and flow and its application in simulation of water-jet slotting enhanced gas drainage

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Abstract. In order to better understand the mechanism of water jet slotting in enhancing gas drainage, based on the Langmuir equation, we constructed an innovative model to simulate the gas release and flow law. The simulation results show that the pressure in the coal seam of the slotting case reduces faster than that without slotting. At 21 day, the gas flow rate from the slotting case is 52% larger than that of without slotting. The gas desorbed from the coal seam not only flows to the borehole but also flows to the rock strata. The decompression and venting area starts near the borehole and gradually extends to the whole area.

1. Introduction

High-pressure water-jet slotting technology is an effective approach and it can improve the coal seam gas drainage rate significantly [1-3], the mechanism of gas drainage enhancement and the gas flow patterns in the coal seam and the adjacent strata are still not fully understood. Knowing the range and extent of gas releasing in the coal seam around the borehole and slot, and how long the pressure will reduce to below the criteria value for a certain design of drainage are beneficial to mining planning safe production. Field trial and laboratory experiments can only provide data from limited observing points, so far a whole picture showing the process of the gas release and propagation of the de-pressure in the coal seam is not available. These have hindered the promotion and application of the slotting technique using high-pressure water jet.

Many researchers proposed models based on finite element method to simulate gas release and migration in coal seam [4-7]. These models focus on the coupling between the gas flow and deformation of solid coal to simulate the distribution of pressure and concentration of methane gas due to gas migration in coal seams. Assuming the gas release and flow is driven by diffusion, there are two popular diffusion models, the ‘unipore’ and ‘bi-disperse’, based on the pore structure of coal. However, in the diffusion modes, in addition to the porosity and permeability of coal seam, an extra parameter, the diffusivity is needed. This added difficulty to the modelling as it is hard to determine the diffusivity of the coal seam. The errors in determining the diffusivity increase the uncertainty of the modelling result.

In this paper, we established a novel model based on Langmuir equation to simulate the process of...
the gas release and flow from the coal-bed into the slot and drainage borehole to investigate the flow dynamics of the gas flow from the releasing. The purpose of the simulation is to reveal the process of the gas release by the borehole, compare the effect of the slotting in enhancing gas release. The simulation model provides a scientific basis for the prediction of gas drainage, evaluation of the gas extraction strategies, and the optimization design of coal seam gas drainage systems.

2. Governing equations of the flow

Assuming the flows in the coal seam are two phases (gas and water), the continuity equation for the mixture is:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = \dot{m} \vec{v}$$

(1)

where $\vec{v}_m$ is the mass-average velocity, and $\rho_m$ is the mixture density, $\alpha_k$ is the volume fraction of phase, $k$, $\dot{m}$ represents mass transfer due to user-defined mass sources.

The momentum equation for the mixture is:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^T)] + \rho_m \ddot{g} + \nabla \cdot (\sum_{k=1}^{2} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k})$$

(2)

The energy equation for the mixture takes the following form:

$$\frac{\partial}{\partial t} \sum_{k=1}^{2} (\alpha_k \vec{v}_k E_k) + \nabla \cdot \sum_{k=1}^{2} (\alpha_k \vec{v}_k (\rho_k E_k + p)) = \nabla \cdot (k_{eff} \nabla T) + S_E$$

(3)

where $k_{eff}$ is the effective conductivity. The first term on the right-hand side of equation represents energy transfer due to conduction. $S_E$ includes any other volumetric heat sources.

In the above equation,

$$E_k = h_k - \frac{P}{\rho_k} + \frac{\vec{v}_k^2}{2}$$

(4)

The coal seam we are modeling is treated as porous media. An additional momentum source term is added to the standard fluid flow equations to represent the resistance of the porous medium to the flow.

$$S = D \mu \nu + 0.5C p \nu^2$$

(5)

The momentum source term is composed of two parts: a viscous loss term (the first term on the right-hand side of equation 5), and an inertial loss term (the second term on the right-hand side of equation 5). The inverse of the coefficient $D$ is the permeability value.

The difficulty is the expression of the source term $\dot{m}$, in equation (1). The most innovative aspects of this study are related to the coupling in the model of the volumetric releasing rate equation with the pressure field and the pressure change rate based on the Langmuir equation, as described below.

3. Desorption rate of gas release

In order to accurately describe the gas release rate, we proposed a method which is rigorously based on the Langmuir equation. The cumulative increase in adsorbed gas with pressure is represented by adsorption isotherms. An adsorption isotherm reflects the premise that adsorbed gas content ($C$) is a function of pressure

$$C = f(p)$$

(6)

The rate of gas content release over time ($t$) with declining pressure ($p$) is defined as the desorption rate.

$$\frac{dC}{dt} = \frac{\partial f(p)}{\partial p} \frac{dp}{dt}$$

(7)

It can be seen that the gas release rate depends upon two parameters. One is the derivative of the Langmuir curve, $\frac{\partial f(p)}{\partial p}$ which is also a function of pressure $p$, and the other one is the change rate of
pressure \( \frac{dp}{dt} \). In other words, gas release is a function of pressure \( p \) and the rate of pressure change.

To determine the gas release rate of coal seam, it is necessarily to know the pressure and the pressure change rate. In an unsteady gas flow in the coal seam domain, however, the pressure \( p \) is different at different points and at different times, there is no analytic solutions for pressure and pressure change rate. Applying equation (7) over the entire finite volume of the coal domain, the complete expression for gas generation is obtained.

Assuming gas sorption obeys the Langmuir isotherm, i.e.

\[
V(p) = \frac{V_L p}{p_L + p}
\]  
(8)

where \( p \) is gas pressure, \( V(p) \) is the amount of gas adsorbed at \( p \). \( V_L \) represents the Langmuir volume parameter: the maximum volume of gas adsorbed as pressure approaches infinity. \( p_L \) represents the Langmuir pressure parameter: the pressure at which the volume of adsorbed gas achieves 50% of the maximum value. From (8), we have:

\[
\frac{dV(p)}{dt} = \frac{V_L p_L}{(p_L + p)^2} \frac{dp}{dt}
\]  
(9)

A program has been written according to Equation (9), and integrated with the commercial code FLUENT as a user defined function and thereby applied to the coal seam domain.

4. Investigation of coal seam gas desorption enhanced by water jet slotting

4.1. Model geometry and meshes

A cylindrical block of strata of 20 m in diameter and 10 m in depth containing coal seam and rock strata is taken as the computation domain for the modeling as shown in Fig.1. A borehole of 200 mm in diameter is drilled perpendicular to the coal seam and a circular slot is generated in the coal seam starting from the borehole. The width of the slot is 100 mm, and the diameter of the circular slot is 2 m.

![Figure 1. Geometries](image)

Assume axisymmetric flow about the axe of the borehole, only half of the geometry is included in the model. The meshed domain is shown in Fig.2. Total mesh number is around 25000. As can be seen in the figure much finer meshes are applied in the borehole and the slot areas because great gradient of pressure occurred in these areas.

4.2. Boundary conditions and initial conditions

The coal seam and roof and floor strata are considered porous medium, the gas flow in these porous
zones is Darcy flow, and permeability of $10^{-16}$ m$^2$ and porosity 3% are assumed. Initial pressure of 2 MPa is assumed before the drilling of the borehole. At the same time, the coal seam is considered a mass source where methane is generated from each finite volume. The generating rate of methane is determined by pressure and the pressure change rate as described in section 3, obeying equation (14), which has been implemented in the solver of the Fluent as a user-defined function. The rock strata are not source, however, it is assumed that the pores of the strata are filled with methane due to gas migration during the long history before drilling. The areas of the borehole and the slot are non-porous zones, and flows in these areas are simulated using k-epsilon turbulent model.

In order to make comparison, flow of non-slotting is also simulated. This is achieved by simply setting the area of slot zone as a porous zone with permeability of $10^{-16}$ m$^2$ as the same as the coal seam. The exit of the borehole is set as a pressure outlet with constant pressure of atmosphere. And the other boundaries of the domain are set as walls. The simulation of the gas release and flow is conducted with ANSYS Fluent. Double precision pressure-based 2D axisymmetric model is applied. The gas emission and flow is a dynamic process, thus transient flow model is applied.

5. Results

Fig. 3 shows the historical changes of pressure in the 2 cases. The pressure in the domain is initially 2 MPa everywhere, and gradually decreases as time going on. In about 22 days (1900000 s), the maximum pressure reduces to below 1.2 MPa in both cases. Pressure reduction starts from the borehole and slot in both cases. It is seen that the significant pressure reduction area in the slotting case is much larger than in the non-slotting case, indicating the slotting can make the coal seam pressure and gas content reduce faster, which benefits to improving mining safety and production.

After 20 hours (72000s) of drainage, it shows that pressure reductions in the coal seam and in the rock strata are totally different. This is because the rock strata do not absorb gas but only contain pressurized free gas, unlike the coal seam where in addition to the pressurized free gas stored in the pores of the coal seam, a large amount of gas is also absorbed to the surface of the coal particles. This is why the pressures in the rock strata are much lower than that in the coal seam although the same permeability is applied to the coal seam and the rock strata.

Fig. 4 compares the velocity profiles of the two cases. It is seen that the high velocity occurs at the areas near the borehole and the slot. The range of high velocity in the slotting case is larger than that of the non-slotting case. It is found that on the interfaces of the coal seam and the rock strata the velocities
are much higher than other places. This is because the pressures of the rock strata reduce faster than in the coal seam, causing larger pressure gradient at the interfaces, which indicates gas released from the coal seam flows not only towards the borehole, but also towards the rock strata.

![Comparison vector distributions after drilling 20 hours](image)

**Figure 4.** Comparison vector distributions after drilling 20 hours

Fig. 5 plots the pressure values at a point A (Fig. 4) which is in the middle of the coal seam and with a distance of 5 meters from the borehole. It is seen that as time going on, the pressure difference of the two cases increases. When the time comes to near 2000000 s (23 days) the pressure at point A in the slotting case is nearly 300000 Pa lower than that at the same point in the non-slotting case, indicating the slotting can accelerate pressure reduction in coal seam.

![Pressure changes with time](image)

**Figure 5.** Pressure changes with time

![Methane flow rates at the borehole](image)

**Figure 6.** Methane flow rates at the borehole

Fig. 6 shows the gas flow rate at the exit of the borehole for slotting and non-slotting cases for a certain time period. It is clearly seen that the slotting really enhanced the drainage flow rate. When drainage time is about 21 days (1820000 s), the flowrate of the slotting case increases 52% over the non-slotting case. The transient model provides information about when the pressure of a certain location will be reduced to a certain value, which will be helpful for optimization of borehole and slotting design and operation.

**6. Conclusions**

(1) A novel mathematical model based on Langmuir equation is derived to describe the desorption of gas from the coal seam and is implemented to software as user defined function.

(2) The simulation results show that when drawing with slotting the pressure in the coal seam reduces faster than that without slot. The slotting significantly increases the gas flow rate at the borehole exit. At 21 day, the gas flow rate from the slotting case is 52% larger than that of without slotting.

(3) The gas desorbed from the coal seam not only flows to the borehole but also flows to the rock strata. The decompression and venting area starts near the borehole and gradually extends to the whole area. The existence of the slot enlarges the range of pressure reduction and gas release. Because the strata do not absorb gas, the pressure in these areas decreases faster than the coal seam, which leads to
the increase of gas desorption in the adjacent strata.

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