Formation and propagation of methane seepage wave in stressed coal

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Abstract

The numerical simulation of filtration streams of gas in a coal layer with allowance for of character of distribution of stresses in a boundary part of a layer is conducted. The numerical algorithm of problem solving about mass transfer of methane to openings in gas content coal seams is developed and realized on the computer. The model of gas seepage in a coal bed has revealed features of the process based on the dependence of coal permeability on effective stresses and adsorbed gas amount. A seepage wave forms in this case; the wave travels in an originally impermeable coal bed, generates permeability zone in it and provides outflow of gas through exposures to mined-out area.

1 Introduction

Underground coal mining is usually faced with the challenging tasks concerned with gas flow analysis. The relevance of such studies grows as mining goes to deeper levels. Large volumes of gas, especially methane, emitting from coal beds into mined-out areas create difficult and, sometimes, hazardous operation conditions in mines.

Among all characteristics of methane mass-transfer in a porous medium of coal, a special place belongs to permeability coefficient connecting gas seepage rate and pressure gradient. Many researchers attempted to determine permeability of coal specimens under varied confining pressure in a laboratory with a purpose of using the results to judge on coal bed permeability and on the permeability variation with rock pressure. Such tests are of interest for qualitative descriptions of mechanisms of change in permeability versus rock pressure. Quantitative estimation of coal bed permeability in the influence zone of rock pressure relaxation needs ad hoc approaches to determining in situ real-time permeability of coal beds. The theoretical basis of the methods to determine apparent permeability of coal beyond influence zones of underground excavations was given in [1], with the exemplified procedure of corresponding tests to be carried out in mines.

The already available findings of theoretical and experimental research have laid foundation for modern understanding of methane mass-transfer in coal beds saturated with gas. Advancement in numerical methods to solve boundary value problems in terms of partial derivatives and the high-performance computers enable

new-level formulation of basic problems on gas seepage in coal beds and allow new mechanisms to be determined with regard to kinetics of methane desorption from coal [2], [3], [4].
It has been shown in [2] that gas-bearing coal beds in a virgin rock mass are impermeable. Permeability zones appear when alteration of the intact state results in opening of fractures in coal beds. Fractures grow with gas outflow. When this happens, pressure in a sealed hole drilled in a coal bed and in a permeability zone around this hole is lower than the natural gas pressure in intact coal.
The key influence on initiation of permeability zones in coal beds is mining-induced alteration of coal bed stress. Stress relaxation and shearing cause joints oriented mainly along the major principal stress, spacing of joints grows, and thus a system of seepage channels connecting pores appears in coal. The zone with such system of channels is gas-permeable. The zone is confined by a certain level of stresses that comparatively fast abate with distance from a mine opening.
Another factor related with initiation and expansion of gas-permeable zone in coal is shrink (volume reduction) of coal substance when adsorbed gas releases. Joints, initially tightly crowded, deform, and spacing grows between them (cleats). When cleats are sufficiently wide, a system of seepage channels is formed as in the case of coal bed relaxation.
Based on the in situ observation data on gas pressure variation in coal beds and reasoning from the analysis of coal shrinkage and swelling in the course of adsorption-desorption, it is shown in [3] that gas flow in coal bed can be considered as a gas seepage wave with a jump in adsorbed gas value at the wave front coincident with the moving boundary of the permeability zone. A determinant in this case is a gas saturation limit $Q*$, at which gaps sufficient for gas seepage (outflow) appear in gas-impermeable part of coal bed.
Inasmuch as $Q*$ is associated with widening of microcracks and gaps between joints, it is naturally dependent on stress state of coal, first of all, then on tectonic damage and gas content of coal, and on gas sorption-storage capacity and adsorption-deformation properties of coal. For this reason, because of considerable variability of damage and sorption properties within a coal bed section, either along the strike or down the dip, the values of $Q*$ at the boundaries of gas-permeable zones will differ. This is one of the main causes for different pressures in closely spaced holes within the same coal bed.

2 Gas seepage model

This section gives details of theoretical notions on formation of permeability in a coal bed under conditions of its natural occurrence.
A volume of coal bed with voids represented by fractures and pores that can be filled with gas is named active porosity and denoted by m apparently, in coal beds:

$$m = m(\sigma, Q). \tag{1}$$

where σ is a certain generalized stress related with fracture opening; Q is the adsorbed gas concentration, i.e. gas amount per unit volume of coal bed. It is noteworthy that these two parameters give a complete characteristic of state of a coal

bed as other characteristics are described in terms of these parameters. For natural rock pressure and natural gas saturation of coal, these parameters are denoted as σ^0 and Q^0, respectively.
Flow of fluid and gas in porous media under effect of pressure difference is characterized by a seepage rate $\overrightarrow{u}$. The seepage rate is defined as the flow rate per unit area of porous medium oriented perpendicularly to the flow direction. As a rule, in permeability zones in coal beds, seepage is a slow flow and, thus, is assumable as inertialess. This fact enables connecting the seepage rate $\overrightarrow{u}$ and the seepage flow pressure p in the form of the linear Darcy law:

$$\overline{u} = -\frac{k}{\mu} grad(p), \tag{2}$$

where k is permeability; μ is viscosity. The value k has the dimension of area and is only related with the geometry of a porous medium. Such geometrical parameters of permeability zones in coal beds are, for instance, representative sizes of open fractures and sizes of joints. These parameters, as the active porosity, depend on stresses and adsorbed gas concentration. Therefore, in coal beds, generally:

$$k = k(\sigma, Q). \tag{3}$$

The coal bed stresses σ, conditioned by the original stress state of rock mass, depend on occurrence depth of the coal bed and can be arbitrary and as like as not plenty high. On the other hand, adsorbed gas is limited in amount by the coal adsorption limit Q^0. Accordingly, the state of coal in the coordinates (Q, σ) is described by an arbitrary point in a half-string $0 < Q < Q^0, \sigma > 0$.
The basic equation of gas seepage in permeability zone is given by:

$$\frac{\partial}{\partial x}\left(\frac{k}{\mu} p \frac{\partial p}{\partial x}\right) = \frac{\partial}{\partial t}\left(m\rho + Q\right), \tag{4}$$

where ρ is the gas density related with the pressure p by the linear equation of state:

$$\rho = \frac{p}{RT}.$$

It follows from (4):

$$\frac{\partial}{\partial x}\left(\frac{k}{\mu} p \frac{\partial p}{\partial x}\right) = \frac{m}{RT}\frac{\partial p}{\partial t} + \frac{\partial Q}{\partial t}. \tag{5}$$

In this case [5]:

$$\frac{\partial Q}{\partial t} = \delta\left[\frac{Q}{b(a-Q)} - p\right]. \tag{6}$$

The diffusive mass-transfer of gas in coal bed is as a rule a slow process; incidentally, desorption kinetics in permeability zone is neglected, i.e., the gas-dynamic state of coal bed is assumed equilibrium at any time, and the corresponding sorption isotherm is used to connect p and Q. In this case, in (5), instead of (6), it is possible to use:

$$\frac{\partial Q}{\partial t} = \frac{ab}{(1+bp)^4}\frac{\partial p}{\partial t}. \tag{7}$$

This case will be discussed below with illustrated generation of a gas seepage wave in an originally impermeable coal bed.
Let the coordinate axis x be connected with the free surface of a semi-infinite coal bed and oriented in line of expansion of a permeability zone. The boundary of this zone is denoted as $\widetilde{x}(t)$.
The initial distribution of coal bed gas pressure is assumed as the natural formation pressure p^0, i.e.:

$$p = p_0, x > 0, t = 0.$$

At the free surface of a semi-infinite bed, it is possible to set pressure or a linear combination of pressure and its normal derivative to the free surface. Consequently, the respective boundary condition in a general form is given by:

$$\alpha_1 p + \alpha_2 \frac{\partial p}{\partial x} = f(t), x = 0, t > 0, \tag{8}$$

where α_1, α_2 are constants; $f(t)$ is a certain function.
In the permeability zone, the distributions of the gas pressure and adsorbed gas concentration, $p(x,t)$ and $Q(x,t)$, are continuous at any time t up to the boundary $\widetilde{x}(t)$. At the boundary, the flow continuity condition should hold true:

$$\widetilde{p}\frac{k}{\mu}\frac{\partial p}{\partial x} = \beta\left(Q^0 - \widetilde{Q}\right)\frac{d\widetilde{x}}{dt}, x = \widetilde{x}(t), t > 0, \tag{9}$$

where

$$\widetilde{p} = p(\widetilde{x}, t), \widetilde{Q} = Q(\widetilde{x}, t), \tag{10}$$

β is a constant.
In the coordinates (σ, Q, k) the relation (3) describes a permeability surface schematically shown in Figure 1. The structural features of this surface and its application are comprehensively discussed in [6].
The equation (4) of gas seepage in coal bed is a quasi-linear equation of thermal conduction relative to the pressure p, where k and m depend on the wanted function p and can be discontinuous functions of the arguments x and t. The permeability k, in view of (3), depends on Q and, eventually, via the sorption isotherm, on the pressure p.
At the present day, the most efficient method to solve quasi-linear equations is the finite difference method. With this method, it is inexpedient to use explicit schemes inasmuch as the stability condition:

$$\tau \leq \frac{h^2}{2max\alpha(y)} \tag{11}$$

requires a very small time increment τ at sound selection of a coordinate increment h.
In connection with this, an implicit scheme is constructed within the accuracy $O(h^2+\tau)$

$$\left(k_i^j p_i^j - k_{i+1}^j p_{i+1}^j\right)\left(p_{i+1}^{j+1} - p_i^{j+1}\right) - \left(k_{i-1}^j p_{i-1}^j - k_i^j p_i^j\right)\left(p_i^{j+1} - p_{i-1}^{j+1}\right) = \frac{2h^2}{\tau} E_i \left(p_i^{j+1} - p_i^j\right). \tag{12}$$

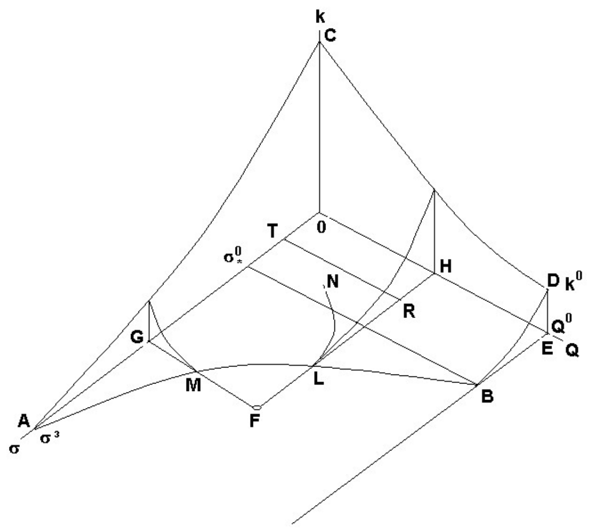

Figure 1: Permeability surface

Simple transformations modify the scheme to suite the double-sweep method:

$$A_i p_{i-1}^{j+1} - C_i p_i^{j+1} + D_i p_{i+1}^{j+1} = -F_i, 0 < i < N, \tag{13}$$

where
$A_i = k_{i-1}^j p_{i-1}^j + k_i^j p_i^j$,
$D_i = k_i^j p_i^j + k_{i+1}^j p_{i+1}^j$,
$C_i = \left(k_{i-1}^j p_{i-1}^j + k_i^j p_i^j\right) + \left(k_i^j p_i^j + k_{i+1}^j p_{i+1}^j\right) + \frac{2h^2}{\tau} E_i$,

$$F_i = \frac{2h^2}{\tau} E_i p_{i^j}. \tag{14}$$

The boundary conditions in the general form may be given by:

$$y_0 = \kappa_1 y_1 + \upsilon_1, \tag{15}$$

$$y_N = \kappa_2 y_{N-1} + \upsilon_2 \tag{16}$$

It is of no particular difficulty to set boundary conditions at the free boundary of the computational domain. In the simplest case, a constant pressure is set (pressure in

open hole or in underground excavation - 1 atm), in other words, $\kappa_1 = 0, \upsilon_1 = p_{hole}$ should be accepted in (15).
At the moving boundary of the permeability zone, the flow continuity condition (9) should be set. Written in the form of (16), it reduces to:

$$y_{N+1} - y_N = \upsilon_2, \tag{17}$$

where
$\upsilon_2 = \dfrac{RT\mu h}{kp_{bound}} M_{bound}$,
T is the absolute temperature of gas; R is the universal gas constant.
The flow M_{bound}, entering the permeability zone from the impermeable zone, is defined by the diffusive flow of gas from coal particles, M_{coal}:

$$M_{coal} = \beta(Q^0 - \widetilde{Q}). \tag{18}$$

With the denotation of the difference scheme:
$Q^0 \Rightarrow q_{N+1}, \widetilde{Q} \Rightarrow q_N$.

The parameter β is a free-varied value characterizing kinetics of gas desorption from coal.
This approach requires continuous positioning of the boundary $\widetilde{x}(t)$, which seems inconvenient as the computational domain undergoes permanent variation and should include fractional cells. This inconvenience many be overcome in the framework of the shock-capturing method. The finite difference scheme should be conservative in this case, which means that the flow continuity condition is automatically satisfied at any point of the domain. The permeability k is assigned to be non-zero in accordance with (3) over the entire mesh and to be zero in the remaining part. With such formulation, the calculation, pursuant to (13), (14), embraces the whole mesh, without identifying the boundary $\widetilde{x}(t)$, which is determined as a jump in the pressure (permeability, adsorbed gas amount, etc.).
The isotherm of methane adsorption by coal is given by the relation:

$$Q = \frac{abp}{1 + bp} \tag{19}$$

at the adsorption parameters $a = 15kg/m^3$, $b = 0.1atm^{-1}$. These values are within the real ranges of the adsorption characteristic of coal.
Furthermore, the permeability surface (3) is given by:

$$k = 10^{-18}\left[\frac{25(1-\overline{\sigma})^2 - Q}{25(1-\overline{\sigma})}\right]^{1.5}, Q \leqslant 15kg/m^3. \tag{20}$$

where $\overline{\sigma}$ is the stress referred to the minimum initial rock pressure when gas outflow is insufficient to induce permeability $(0 \leqslant \overline{\sigma} \leqslant 1)$.
The gas-saturation limit Q^* is related with the stress set as $\overline{\sigma}$ as follows: $Q^* = 25(1-\overline{\sigma})^2$

Obtained in such a manner, the surface, which is the boundary of the permeability zone in coal bed, has the form as in Figure 1 and is qualitatively described by the relation (20). A quantitative description of this surface in actual coal strongly needs experimentation, which calls for special equipment and proper procedures. There are almost no such data available at present time.

3 Results and discussion

The calculations of the parameters of gas flow in underground excavations within the developed approach trace the time variation in the state and dimension of the permeable zone in coal bed ($0 \leqslant x \leqslant \widetilde{x}$); the left-hand boundary $x = 0$ of this zone is the excavation surface, and the right-hand boundary $x = \widetilde{x}$ is the moving front of the permeable zone. Initially, at $t = 0$ an exposure is instantly created, i.e. the excavation wall is made, and gas outflow from coal starts in accordance with the laws (4)-(10).

The parameters that determine the coal bed state at the initial time are:$p = p_0 = 50atm$, $Q = Q_0 = 12.5kg/m^3$, $m = m_0 = 0.03$, and the initial stress $\overline{\sigma}(x)$ included in (20) ranges from 0 to 1. For another thing, it is assumed that at the initial time the rock mass adjoining the exposure undergoes partial stress relaxation. The consequent assumption says that in the stress relaxation zone, $\overline{\sigma}(x)$ linearly grows from zero value at the exposure ($x = 0$) up to a certain maximum at $x = 0.5$ m. Beyond this zone ($x > 0.5$) m, rock mass is in the initial stress state.

The most significant parameter is the gas flow rate in a hole or in an excavation, and the time variation in the rate. This is nearly a single characteristic measurable directly in field conditions. By comparing with this parameter, it is possible, to a certain degree, to adjust problem input parameters which are impossible to determine experimentally.

Figures 2 and 3 show time dependences of gas emission rate and total gas outflow in mine in logarithmic coordinates for the selected values $\overline{\sigma} = 0.0$, 0.1, 0.4, 0.5, 0.6, 0.7.

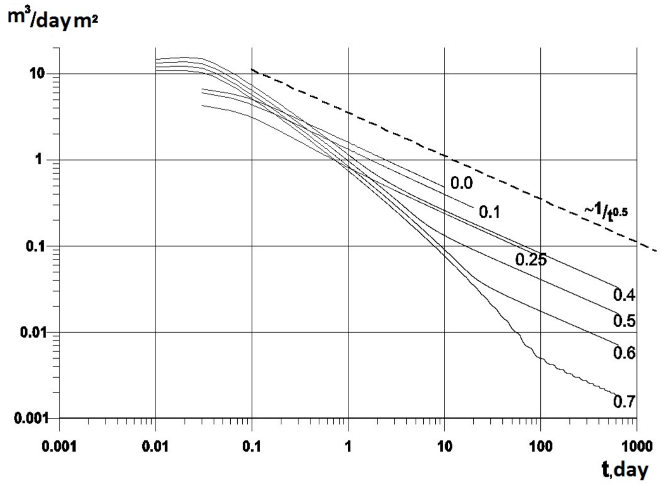

Figure 2: Gas emission rate

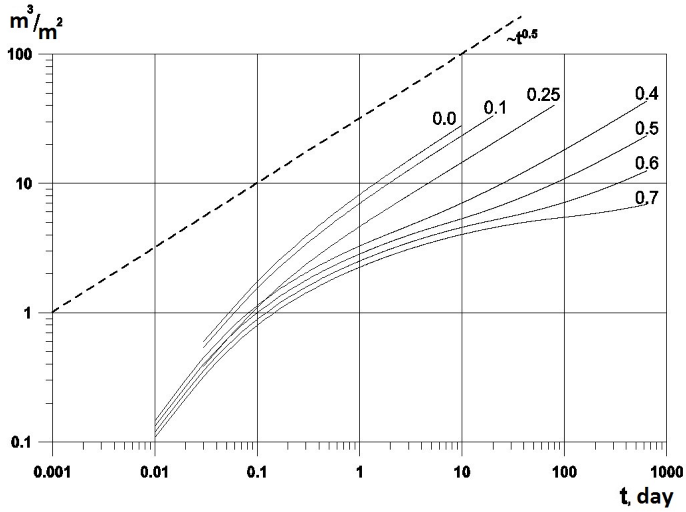

Figure 3: Total gas outflow in mine

A feature of this theory of seepage is the fact that gas seepage takes place only in a limited zone adjoining coal exposure. This zone continuously enlarges with time, which is illustrated in Figure 4 for various values of $\overline{\sigma}$. Figures 5 and 6 give plots

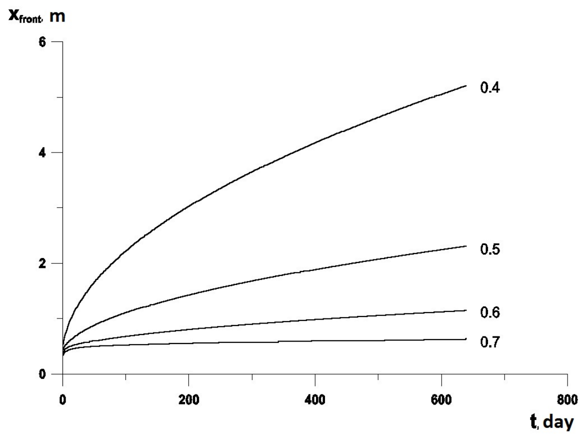

Figure 4: Gas seepage zone enlarge with time

of gas pressure and permeability distributions in the mentioned zone at different times at $\overline{\sigma} = 0.4$. There are two clear sub-zones within the permeability zone: in one sub-zone permeability is generated by stress relaxation of coal at the exposure ($0 < x <\sim 0.5m$), in the other sub-zone permeability is the consequence of gas desorption and outflow from coal.

These seepage calculations assume that stresses are independent of time; in other words, coal shrinkage due to gas outflow and the associated redistribution of stresses in overlying rock mass are neglected.

In case that initial stress is relatively low (in the case analysed, $<\sim 0.28$), coal bed, in line with (2), becomes permeable at any t irrespective of adsorbed gas amount Q. Otherwise (i.e. when $\overline{\sigma}(x) > 0.28$), stress relaxation induces permeability in a certain area where $Q < Q(\sigma)$. Outside this area coal bed remains impermeable and its state can only alter with the reduction in Q with time.

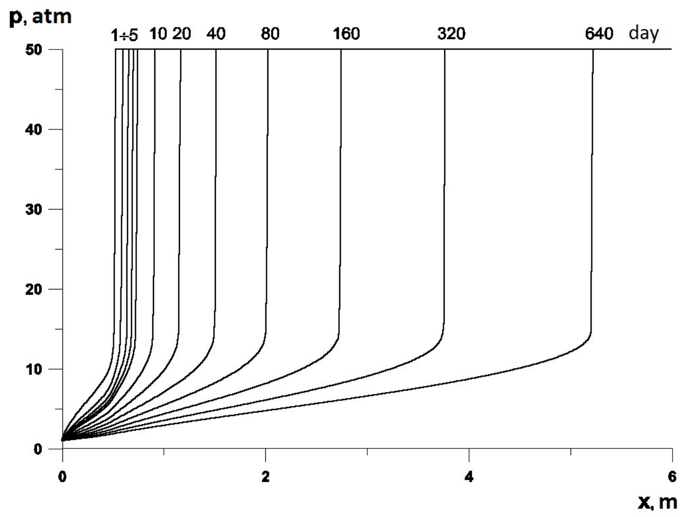

Figure 5: Gas pressure distribution at different times

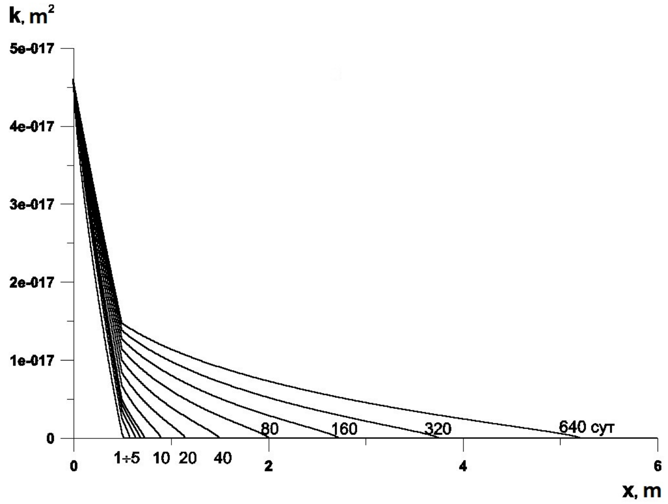

Figure 6: Permeability distribution at different times

4 Conclusions

The model of gas seepage in a coal bed has revealed features of the process based on the dependence of coal permeability on effective stresses and adsorbed gas amount (see Figure 1). A seepage wave forms in this case-it is clearly seen in Figure 5; the wave travels in an originally impermeable coal bed, generates permeability zone in it and provides outflow of gas through exposures to mined-out area.

The seepage wave travel to a great extent depends on effective compressive stresses. From the analysis of this dependence, it is concluded on the limitedness of dimension of the permeability zone and, as a consequence, on the finiteness of gas emission in mined-out area.

The accepted gas pressure in an underground excavation (at the left-hand boundary of the computational domain) is 1 atm. In line with the sorption isotherm (19), this pressure fits with adsorbed gas amount $Q = 1.36 kg/m3$, which, in its turn, on the strength of (20), agrees with the constraining stress $\overline{\sigma} = 0.766$. This means that when calculations assume maximum stress as equal or higher than 0.766, the behaviour of gas seepage changes cardinally. In this case, the permeability zone extends until the stress at the zone front reaches the value 0.766. From then on, dimension of gas-drained area in coal bed remains unchanged and pressure here drops down to 1 atm. Supposing coal bed stress originally exceeds 0.766 (for the parameters accepted in the present calculations), seepage does not start at all, and slow diffusive escape of gas from coal takes place.

Acknowledgements

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