
**KINETICS OF METHANE PENETRATION INTO A SPACE
ADJACENT TO A POROUS SOLID BODY**

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Main stages of a gas release from a porous solid body are considered, and the dependences of the gas concentration on time in the air on each of the stages are determined. For the case of the methane release from a coal substance, the quantity of the released methane is determined along with a time needed for the gas dangerous concentration to be reached in an excavation room. It is established that the average concentration of methane in the air and the characteristic transient period of time weakly depend on the methane-in-air diffusion coefficient; instead, these are determined mainly by the coal massif parameters.

Introduction

During a metamorphism, the formation of methane and its partial accumulation in a coal-bed had taken place. At present time, a reverse process, in a definite sense, is going on: a methane release (in a more or less degree) occurs when a mining work is carried out in coalmines [1, 2]. Because of this, a phenomenon of the gas (in particular, methane) release from coal-beds is an important problem associated with such topical issues as the environment protection, mine works safety, and others.

This paper relates to the field of coal physics and is a continuation of the previously published work [3] devoted to the kinetics of methane absorption/release in the coal substance. The work addresses the urgent problem of formation of the methane explosive concentration in coalmine excavations. This phenomenon, unfortunately, leads to methane explosions in coalmines and killing of miners.

The methane release process and, as a consequence, the formation of its dangerous concentration, depend on

a number of natural and man-caused factors, such as the gas content in a coal-bed, distribution of the gas amongst various gas-state phases, porosity (opened and closed), gas permeability of a coal-bed, etc.

1. General Relationships

Let us consider a methane release from a semi-infinite bed of porous coal into an air-filled room. Distribution of methane in the coal substance is described by concentration $c(x, t)$. Movement of methane molecules inside the solid solution occurs because of diffusion characterized by diffusion coefficient D_1 . When leaving the solid body, gas molecules move to the air completely, without being precipitated on the gas/solid body interface. The distribution of methane molecules in the confined air-filled room of L width is characterized by density $\rho(x, t)$ and diffusion coefficient D_2 .

Let us consider a case in which gas molecules intercept the interface (Fig. 1). A stream of particles flowing through boundary $J_1(0, t)$ from the porous solid body can be written as [3, 5]:

$$J_1(0, t) = \frac{D_1}{\sqrt{\pi D_{\text{eff}}}} \frac{d}{dt} \int_0^t \frac{c_0 - c(0, \tau)}{\sqrt{t - \tau}} d\tau, \tag{1}$$

where c_0 is the concentration of methane molecules in the solid solution far from the boundary,

$$D_{\text{eff}} = \frac{D_1}{1 + \gamma/\nu} \tag{2}$$

is the effective diffusion coefficient of methane in the porous coal substance, γ — porosity, and ν — solubility of methane in a coal.

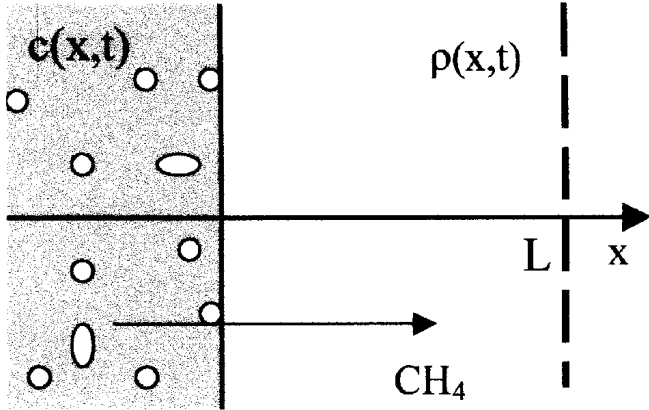


Fig. 1. Schematic drawing of movement of methane molecules from a coal substance into a confined air-filled room

A stream of particles flowing through the interface into the air-filled room can be written analogously:

$$J_2(0, t) = \sqrt{\frac{D_2}{\pi}} \frac{d}{dt} \int_0^t \frac{\rho(0, \tau) - \rho_m(\tau)}{\sqrt{t - \tau}} d\tau, \quad (3)$$

where

$$\rho_m(t) = \frac{1}{L} \int_0^L \rho(x, t) dx \quad (4)$$

is the average concentration of methane in the air medium. In supposition that all the molecules released from the porous solid body pass into the confined room, that is, streams (1) and (2) are equal to each other, and taking into account that

$$c(0, t) = \nu \rho(0, t) \quad (5)$$

(provided that the chemical potentials at both the interface sides are equalized instantly [6]), we get the following relationship between the concentration of gas molecules at the gas/solid body interface and the average concentration of the gas at the same moment of time:

$$\begin{aligned} \frac{D_1}{\sqrt{\pi D_{\text{eff}}}} \frac{d}{dt} \int_0^t \frac{c_0 - c(0, \tau)}{\sqrt{t - \tau}} d\tau = \\ = \sqrt{\frac{D_2}{\pi}} \frac{d}{dt} \int_0^t \frac{\rho(0, \tau) - \rho_m(\tau)}{\sqrt{t - \tau}} d\tau. \end{aligned} \quad (6)$$

However, it should be noted that Eq. (6) is true if the diffusion permeability of the interface is high. After transformations, we obtain

$$\rho(0, t) = \frac{c_0 + \beta \rho_m(t)}{\nu + \beta}, \quad (7)$$

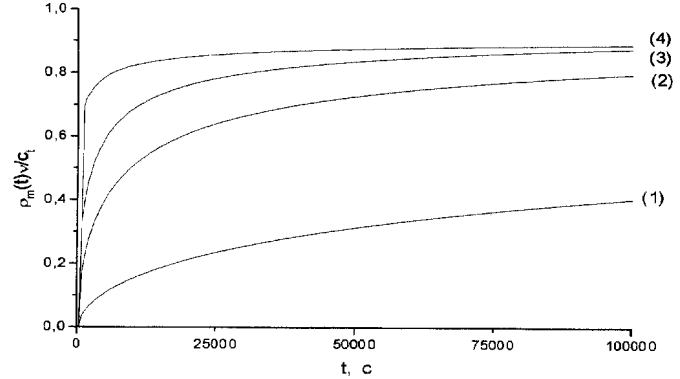


Fig. 2. Evolution of the methane average concentration in air in time at various values of solubility ($D_1 = 10^{-10} \text{ m}^2/\text{s}$; $D_2 = 2.5 \cdot 10^{-5} \text{ m}^2/\text{s}$; $c_t = 25 \text{ mM}/\text{m}^3$; $L = 1 \text{ m}$; $\gamma = 0.1$): $\nu = 0.001$ (1), 0.005 (2), 0.01 (3), and 0.03 (4)

where $\beta = \sqrt{D_2 / (D_1 (1 + \gamma/\nu))}$.

Now let us write the material balance equation that follows from the law of conservation of the total number of particles in the system:

$$\frac{d\rho_m(t)}{dt} = \frac{1}{L} \sqrt{\frac{D_2}{\pi}} \frac{d}{dt} \int_0^t \frac{\rho(0, \tau) - \rho_m(\tau)}{\sqrt{t - \tau}} d\tau. \quad (8)$$

In fact, Eq. (8) describes a replenishment of the air room with methane molecules releasing only from the porous solid body. Eqs. (7) and (8) define the final form of the integral equation describing the dependence of the average concentration of the room-contained gas on time:

$$\rho_m(t) = \frac{1}{L} \sqrt{\frac{D_2}{\pi}} \int_0^t \frac{\rho(0, \tau) - \rho_m(\tau)}{\sqrt{t - \tau}} d\tau, \quad (9)$$

or, in view of (8), we have

$$\rho_m(t) = \frac{1}{L(\nu + \beta)} \sqrt{\frac{D_2}{\pi}} \int_0^t \frac{c_0 - \nu \rho_m(\tau)}{\sqrt{t - \tau}} d\tau. \quad (10)$$

This integral equation permits us to obtain, by applying the asymptotic analysis, an explicit form of dependence of the average gas concentration on time at various stages of the gas release process. Hence, the analysis of experimental data and their comparison with prediction (Fig. 2) is made, in the most part, to be simpler.

2. Asymptotic Dependences and Numerical Estimations

At the initial stage of the gas release process, when the gas average concentration in air is much less than the equilibrium one, an increase of the concentration is observed to be in compliance with the $t^{1/2}$ law:

$$\rho_m(t) = 2 \frac{c_0}{L(\nu + \beta)} \sqrt{\frac{D_2}{\pi}} t^{1/2}. \quad (11)$$

This form of dependence is conserved within time periods much lesser than the characteristic time t_* which represents a time gap needed for the gas concentration in the air space to reach a value comparable with the equilibrium one:

$$t_* = \frac{L^2}{D_2} \left(1 + \frac{\beta}{\nu}\right)^2. \quad (12)$$

Concentration of the gas in air approaches its equilibrium value at $t \gg t_*$ in the inverse proportion to $t^{1/2}$:

$$\rho_m(t) \approx \frac{c_0}{\nu} \left(1 - \frac{L(\nu + \beta)}{\nu\sqrt{\pi D_2}} t^{-1/2}\right). \quad (13)$$

Hence, two main phases of the gas release are set off and a concentration comparable with the equilibrium one is reached already at the end of the first of them.

Asymptotic dependences (11) and (13) allow estimation, with using gas-content data for a specific sort of coal, of time needed to achieve a maximal permissible concentration of methane in an excavation if one issues from considerations of the accident prevention in mining works:

$$t_{\text{crit}} = \frac{\pi}{4} \frac{L^2(\nu + \beta)^2}{c_0^2 D_2} (\rho_m^{\text{crit}})^2. \quad (14)$$

We can simplify even more the obtained relationships if we take into account the real relations between the values characterizing the coal substance. To obtain numerical estimations, let us take the coal-bed porosity to be $\gamma = 0.25$, and the solubility of methane molecules in coal to be $\nu = 0.01$. As the previous calculations and experimental data show, these parameter values are quite commonly used and correspond to the real characteristics of coal [7]. We suppose the methane-in-coal diffusion coefficient to be equal $D_1 = 10^{-6} \text{ cm}^2/\text{s}$ and the methane-in-air diffusion coefficient $D_2 = 0.25 \text{ cm}^2/\text{s}$. The total concentration of methane in coal equals the methane-content ability of the latter, and we take it as $c_t = 25 \text{ mM/m}^3$ (characteristic of a large group of

coal sorts). Methane concentration c_0 at infinity inside the solid solution is connected with the in-coal methane concentration c_t by the relationship [3]

$$c_t = c_0 \left(1 - \gamma + \frac{\gamma}{\nu}\right). \quad (15)$$

If one takes into account that $\gamma \gg \nu$, then $c_0 = (c_t \nu) / \gamma$.

At the initial moment, the concentration of methane in air equals zero. For short time intervals, the average gas-in-air concentration evolves as

$$\rho_m(t) \approx \frac{2c_t}{L} \sqrt{\frac{\nu D_1}{\pi \gamma}} t. \quad (16)$$

The characteristic time period during which this dependence is valid, is

$$t \ll t_1 \approx \frac{L^2}{D_1 \nu \gamma}. \quad (17)$$

With the above-mentioned usual parameters of a coal substance, the estimation for an excavation room of several-meter size gives a value of about 10^{10} s for duration (17) of the first gas-release stage, i.e., the extremely large value.

For large time intervals, $t \gg t_1$, the same approximation and numerical parameters give the average methane concentration to approach the equilibrium value in accordance with the formula

$$\rho_m(t) \approx \frac{c_t}{\gamma} \left(1 - \sqrt{\frac{L^2}{\pi D_1 \nu \gamma}} t^{-1/2}\right). \quad (18)$$

In this case, the time needed to reach the maximal admissible concentration of gas in the air (about 1.3 %) equals

$$t_{\text{crit}} \approx (\pi/4)(L^2 \gamma \rho_{\text{crit}}^2) / (c_t^2 \nu D_1) \approx 11 \text{ h}. \quad (19)$$

Conclusions

Since the duration of the initial gas-release stage turns out to be, as follows from the above numerical estimation, dramatically large, then this is the first stage of the process that is, as a rule, observed in practice. Moreover, it is also seen that the average concentration of methane in air and its characteristic settling time do not depend on the methane-in-air diffusion coefficient but, instead, are determined mainly by the parameters of a coal massif.

Experiments in coalmines [8] show that, under the conditions of methane release from a coal substance, the equilibrium concentration of gas in air ρ_m^e turns out, as a rule, higher than the maximal admissible one, $\rho_m^{\text{crit}} < \rho_m^e$. But if the methane content in a coal-bed is low (or when a gas releases from other porous materials such as metals with gas-filled pores and cracks), i.e., at $c_0 < \nu\rho_{\text{crit}}$, certain values of the gas concentration in air could not be achieved at all.

On the other hand, under extreme conditions, such as in the neighborhood with an inflammation point, a temperature increase and the presence of higher homologs of methane [9] may cause a shortening of the time period needed for achievement of the critical concentration up to several minutes.

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КІНЕТИКА ЗАПОВНЕННЯ МЕТАНОМ ПОВІТРЯНОГО
ПРОСТОРУ, ЩО МЕЖУЄ З ПОРИСТИМ
ТВЕРДИМ ТІЛОМ

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Р е з ю м е

Розглянуто головні стадії виділення газу з пористого твердого тіла, яке його містить, та визначено залежності від часу концентрації газу в повітрі на кожній з цих стадій. Для випадку виділення метану вугільною речовиною визначено кількість метану, що виділився, та час, за який досягається небезпечна концентрація газу у просторі виробки. З'ясовано, що середня концентрація метану в повітрі та характерний час її встановлення слабо залежать від коефіцієнта дифузії метану в повітрі, а визначаються, головним чином, параметрами вугільного масиву.