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MATHEMATICAL MODEL OF METHANE EMISSION CAUSED BY A COLLAPSE OF ROCK MASS CRUMP

O MODELU MATEMATYCZNYM EMISJI METANU WYWOŁANEJ TĄPNIĘCIEM GÓROTWORU

Rock mass collapses in mines containing gas are accompanied by an intensive outflow or discharge of methane. Movement of this gas through the ventilation network results in disturbances of the methane concentration distribution in sectors of the mine ventilation network and may lead to an explosion hazard.

This article presents a mathematical model of methane emission following a collapse. It discusses the mechanics of the phenomenon of collapse and its gas dynamics. Two key sources of methane emission have been identified:

- release of gas from fragments of side wall rocks transported into the working,
- filtration inflow of gas to the working through the stress-relieved zone formed as a result of the rheological process and the rock mass beyond that zone.

For the methane release from coal fragments the four-component emission model proposed by Airuni (1987) has been used, which includes methane emission from the volume of sorbed particles, the surface of these particles, supersorbed particles and filtration-sorbed particles. The paper presents parameters of individual components of the emission. It has been demonstrated that the last component with the highest time constant has a significantly larger share in the total gas absorbability than components with lower time constants. For the gas inflow from the stress-relieved zone and the rock mass the *filtration* flow model has been adopted (Tarasow, Kolmakow 1978), which includes the depth of the stress relieving zone variable in time, the porosity coefficient and permeability coefficient as a function of porosity and gas pressure. On the basis of this model and with the use of results of experimental research of changes in the rate of gas release during the formation of the stress-relieved zone, the initial velocity of methane release has been approximated by the exponential function. By adding both sources of methane emission, the total stream of gas volume flowing to the working in the collapse zone was calculated in relation to a length unit of the working.

The presented model of methane emission following a rock mass tremor or collapse and the formulation of the mathematical model of the air and methane mixture distribution in the mine ventilation network will allow for developing professional software simulating the aforementioned phenomena.

Key words: mine ventilation, rock mass crump, mathematical model

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W kopalniach gazowych tąpaniom towarzyszy silny wypływ lub wyrzut metanu. Unoszenie tego gazu drogami wentylacyjnymi jest przyczyną zmian rozkładu stężenia metanu w bocznicach sieci wentylacyjnej kopalni i może spowodować zagrożenie wybuchem.

W artykule przedstawiono model matematyczny emisji metanu związanej z tąpnięciem. Omówiono mechanikę zjawiska tąpania i jego gazodynamikę. Wyróżniono dwa podstawowe źródła emisji metanu:

- wydzielanie się gazu z okruchów skały ociosów przemieszczonych do wyrobiska,
- filtracyjny dopływ gazu do wyrobiska przez nowo formowaną w procesie reologicznym strefę odprężenia i górotwór poza tą strefą.

Dla wypływu metanu z pokruszonego węgla przyjęto czteroskładnikowy model emisji podany przez Airuni'ego (1987), uwzględniający emisję metanu z objętości cząstek sorpcyjnych, z powierzchni tych cząstek, z cząstek supersorpcyjnych i z cząstek filtracyjno-sorpcyjnych. Podano parametry poszczególnych składowych emisji i pokazano, że ostatnia składowa, o największej stałej czasowej, ma znacznie większy udział w całkowitej gazonośności niż składowe o mniejszych stałych czasowych. Dla dopływu gazu ze strefy odprężonej i górotworu przyjęto model przepływu filtracyjnego (Tarasow, Kołmakow 1978), uwzględniający zmienną w czasie głębokość strefy odprężenia i współczynnik porowatości oraz współczynnik przepuszczalności jako funkcję porowatości i ciśnienia gazu. Na podstawie tego modelu, korzystając również z wyników eksperymentalnych badań zmian szybkości wydzielania się gazu w okresie formowania strefy odprężenia, aproksymowano funkcją wykładniczą początkową prędkość wydzielania się metanu. Sumując obydwa źródła emisji metanu wyznaczono całkowity strumień objętości gazu dopływającego do wyrobiska w strefie tąpnięcia, odniesiony do jednostki długości wyrobiska.

Przedstawiony model emisji metanu związanej z wstrząsem lub tąpnięciem górotworu oraz sformułowanie matematycznego modelu rozpływu mieszaniny powietrza i metanu w sieci wentylacyjnej kopalni pozwoli na opracowanie profesjonalnego programu symulacji rozpatrywanych zjawisk.

Słowa kluczowe: wentylacja kopalń, tąpnięcie górotworu, model matematyczny

1. Introduction

Determination of the non-stationary distribution of air and methane mixtures in a mine ventilation network under conditions defined as emergency or disaster is of paramount importance for working safety in mines. The ventilation system control methodology used in practice is to attempt to predict the course of events with the use of computer simulation of the phenomena that occur under these conditions.

A new issue, which has not yet been included for forecasting the distribution of the air and methane mixture in the working network, is an effective mathematical description of methane emission after a rock-collapse and the effects of the methane inflow on the distribution of methane concentrations in mine workings. Therefore, this article discusses the following issues:

- analysis and assessment of the mechanics of rock-falls in the context of methane emission;
- gas dynamics during rock-falls — its mathematical model:
  - release of methane from elements of a damaged coal seam that affects the gas-structure in the working,
  - flow of methane through the stress relieved zone,
  - flow of methane through the rock mass beyond this zone,

– effects of methane on the newly-exposed coal seam surface.

The formulation of the mathematical model of methane emission that includes all the aforementioned phenomena will allow for the computation of values of methane inflows caused by a rock mass collapse.

2. The mechanics of rock-collapse

The international classification of dynamic phenomena (Dubiński, Konopko 2000) includes sudden rock-falls among phenomena whose source is the energy built up in a damaged element of the rock mass. According to applicable Polish regulations, a rock-collapse is a sudden release of elastic strain energy accumulated in the rock mass in the form of tremors in the rock mass, which transfer significant amounts of energy, accompanied by acoustic phenomena and a shock wave. This phenomenon results in damage to the rock structure of roofs, floors and seams, with simultaneous dynamic movement of rocks towards the working and damage or destruction of the working environment or to machinery and equipment.

The physical operation of workings disturbs the natural distribution of stresses in the rock mass. Vertical stresses in the working sidewalls increase, whilst in the floor and roof tensile stresses occur build up. According to J. Znański (1964) after exceeding the limit of elasticity, the splitting of rocks occurs in their sedimentation planes. In rocks that deform in an elastic and viscous manner, the energy of elastic deformation is partially dissipated and partially converted into kinetic energy of movement between grains and between parts of the rock on either side of its fracture zone as well as into the surface energy of micro-cracks, which then join up and develop into crevices. The remaining portion of the in elastic strain energy is expended as kinetic energy of in the separate integuments created this way, which move towards the working. This energy converts into friction and deformation of the working. The zone of damage moves towards the centre of the rock mass, together with maximum stresses, which thus are released. The speed of the destruction zone's movement and depth are dependent on the structure of the rocks that surround the working. Accompanying deformations usually are manifested by increased static pressure of the working's walls and its their contraction. If due to any reason (e.g. working operation) the stresses and loadings on rock areas within the zone of destruction increase, rock-burst may occur.

According to W. Parysiewicz (1966), the category of a collapse depends on the strength ratios of the roof/seam/floor system.

If the strength of the roof is greater than the strength of the seam and the floor, with the latter having similar strengths, the following situations may occur:

- heavy damage to the seam with little damage to the floor,
- heavy damage to the floor with little damage to the seam,
- heavy damage to the seam and the floor,
- little damage to the seam and the floor.

If the strength of the roof, seam and floor is similar, various combinations of heavy and little damage to the seam, roof and floor may occur, depending on other properties of the rocks. Pure roof collapses, with sudden damage to the roof's rocks towards the working, are relatively rare. The most frequent are seam and floor collapses or a combination of both (Fig. 1).

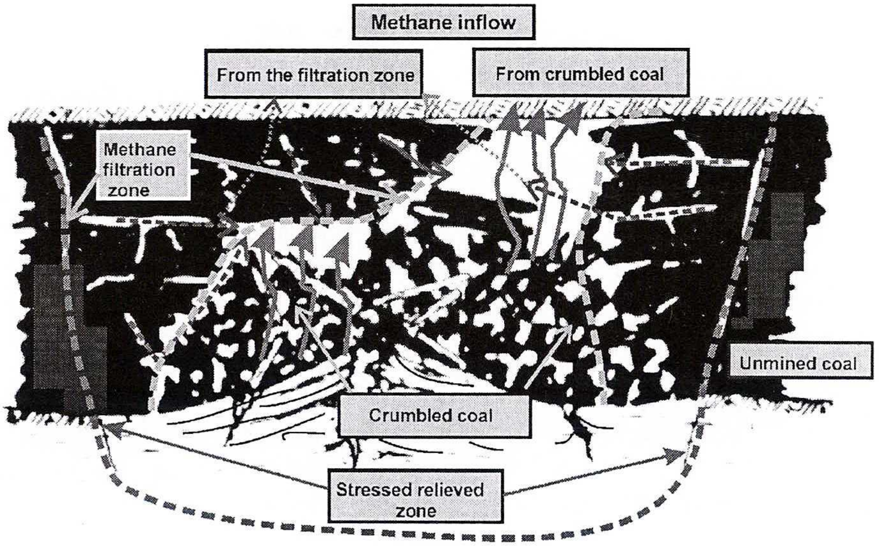

Fig. 1. Cross-section of the crump zone in the coal seam to the working; zones of methane inflow

Rys. 1. Przekrój poprzeczny przez strefę tąpnięcia w pokładzie węgla do wyrobiska chodnikowego; strefy dopływu metanu

A catastrophic rock-burst usually results in damage to the area surrounding the working, the latter becoming filled with rock chippings, whose size is contingent on the seam structure. For heavy roof collapses, the movement of material creates powerful air movements, which may have, devastating effects. The subsidence time of the rock mass (i.e. the time to reach a new balance) may extend over several hours.

3. Gas dynamics of sudden collapses

In gas mines containing high concentrations of gas, collapses are accompanied by a heavy release or discharge of gases (Budryk 1952). The following sources of gas can be separately identified:

- release of free and sorbed gas from fragments of damaged sidewall rock which then moves into the working,
- filtration gas flow to the working through the stress relieved zone, which has been formed in the rheological process, and the rock mass beyond this zone.

In methane-rich mines the release of gas stored in coal is of particular importance. Therefore, below we discusscases of tremors where the damaged and displaced rock of the sidewalls or the floor was coal.

3.1. Release of gas from crumbled coal

Release of gas from crumbled coal is a very complicated process. It involves such phenomena as capillary, molecular and surface diffusion. There is also a strong correlation between the level of fragmentation of the coal and the rate of methane release. Conversely, the greater the proportion of coal in the overall rock-mass, the higher the level of methane retention.

The issue of the correlation between gas release intensity and the coal fragmentation level was theoretically analysed by J. Litwiniszyn (1987), who solved the diffusion equation using the system of spatial polar coordinates.

$$\frac{\partial C}{\partial t} = D_d \left(\frac{d^2 C}{dr^2} + \frac{2}{r} \frac{\partial C}{\partial r} \right) \tag{1}$$

for initial and boundary conditions

$$C(a,t) = C_0 \text{ and } C(r,0) = C_p$$

where:

- a — grain radius,
- C_0 — gas concentration on the grain surface,
- C_p — initial gas concentration with original gas capacity G_g, specified by the following formula:

$$G_g = \frac{4}{3} \pi a^3 C_p \tag{2}$$

While analysing sets of space grains of various radii contained in the same volume, J. Litwiniszyn concluded that the total amount of gas released is not dependent on the degree of size reduction, but with the increasing size reduction the rate of diffusive release of gas grows. Although the total amount of gas released is not directly dependant on the overall diminution in grain size, the *rate* of gas release is connected with the speed of destruction — i.e. rate of reduction of grain size.

A.T. Airuni (1987) analysed the phenomenon of gas release from coal as a multi-step diffusion of sorbed gas from a coal mass unit and its transport by various types of channels existing in coal chippings. The volume of the gas released from a coal mass unit in the function of time t is described by the following formula:

$$V_g = \sum_{i=0}^{3} V_i \left(1 - e^{-\frac{t}{\tau_i}} \right) \tag{3}$$

where:

V_g — total volume of desorbed gas until t,
V_0, τ_0 — desorbed gas volume and desorption time-constant from the volume of sorbed particles,
V_1, τ_1 — sorbed gas volume and desorption time-constant for gas cumulated on the surface of sorbed particles,
V_2, τ_2 — sorbed gas volume and desorption time-constant for supersorbed particles,
V_3, τ_3 — sorbed gas volume and desorption time-constant for filtration-sorbed particles,

where:

$$\tau_0 > \tau_1 > \tau_2 > \tau_3$$

The stream of methane desorption volume from a mass unit of damaged coal is described by the following formula:

$$G_g = \frac{dV_g}{dt} = \sum_{i=0}^{3} G_i e^{-\frac{t}{\tau_i}} \tag{4}$$

where:

$$G_i = \frac{V_i}{\tau_i}$$

The time-constant τ_0 is in the order of many days, τ_1 — hours, τ_2 — dozens of minutes, and τ_3 — minutes. Both time-constants τ_i and gas volumes V_i are different for various degrees of coal size reduction. Airuni presents an experimental calculation of values of the aforementioned time-constants for several groupings of coal size reduction in the range between 0.075 and 4 mm.

The calculated values of τ_1 vary between 2 h and 3 h, values of τ_2 between 20 and 23 minutes, and values of τ_3 between 2.3 and 2.5 minutes.

For the gas volume V_i these values are as follows:

- for V_1 — between 2.8 and 4.35 ml/g,
- for V_2 — between 1.4 and 3 ml/g,
- for V_3 — between 0.5 and 1.65 ml/g.

F.S. Klebanow in (1974) presents measurements of the rate of gas release from mined coal obtained by E.S. Zupachin and N.I. Ustinow for fractions 0.25–0.5 mm and 15–20 mm in the time range between one tenth and one hundredth of a minute. Time-constants of the decreasing gas release rate from these size-categories are 71.5 minutes and 66.5 minutes respectively, whereas approximated initial rates of gas release are approximately 0.012 $\frac{\text{ml}}{\text{g} \cdot \text{min}}$ for the finer fraction and 0.004 $\frac{\text{ml}}{\text{g} \cdot \text{min}}$ for the oarser fraction. No data about the time-constant τ_0 and gas volume V_0 is available Here results of research of the methane release rates from mined coal conducted by W. Cybulski and J. Sobala and presented by B. Kozłowski in (1972) can be used. These measurements were carried out for the coal storage time from 24 hours to more than 30 days. Fig. 2 shows the change in methane release in the function of time, based on the aforementioned results.

Taking into account values of τ_1, τ_2, τ_3 for times longer than 24 hours, the equation (4) can be converted as follows:

$$G_0 = \frac{V_0}{\tau_0} e^{-\frac{t}{\tau_0}} \tag{5}$$

or in the logarithmic-linear scale as follows:

$$\ln G_0 = \ln\left(\frac{V_0}{\tau_0}\right) - \frac{t}{\tau_0} \tag{6}$$

On the basis of Fig. 2 it can be easily calculated that:

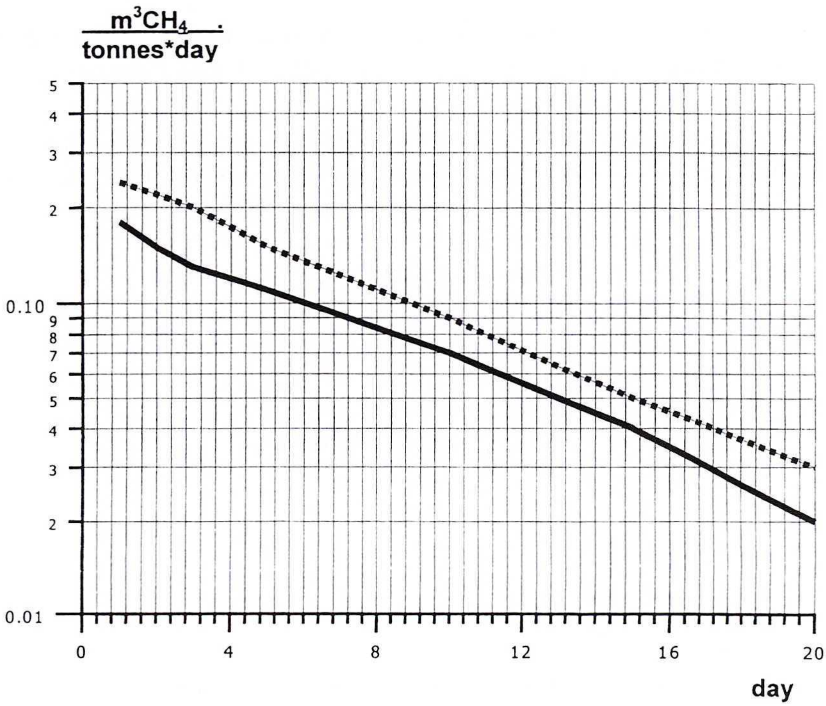

Fig. 2. Methane release rate from mined coal in the function of time

Rys. 2. Prędkość wydzielania się metanu z urobionego węgla w funkcji czasu

$$G_0 = \frac{V_0}{\tau_0} \approx 0.25 \frac{\text{ml}}{\text{g} \cdot \text{min}}$$

and

$$\tau_0 \approx 108 \text{ days}$$

Hence

$$V_0 \approx 27 \frac{\text{ml}}{\text{g}}$$

On the basis of these data it can be concluded that the gas capacity component that corresponds to the highest time-constant has a much higher share in the total gas capacity of crumbled coal than short-term components.

3.2. Gas flow through the stress relieved zone and rock mass beyond this zone

3.2.1. Discharge of gas from open surface of the coal seam

As a result of a collapse, a new stress relief zone is formed that surrounds the area filled with loose chunks and fragments of coal. The calculation of an instantaneous value of methane release from this zone's surface is a complex issue.

Concerning methane release from exposed, un-mined coal resulting from the gradual gas release from the coal seam, there is a large number of books in Polish and foreign literature. They include experimental data and results of approximate solutions of the methane percolation equation in a porous medium. For example, in his paper B. Kozłowski (1974) presents results of experimental research, which indicate that after a relatively constant methane release level from open unmined coal during the first month, the rate of methane release halves in each subsequent month. In his paper J. Pawiński (1971) quotes a number of results of experimental research conducted by Russian scholars, which demonstrated that the methane release intensity from open unmined coal changes according to the following formula:

$$q = \frac{A}{\sqrt{t}} \tag{7}$$

where:

t — time.

In the same publication (Pawiński 1971), starting with equations of continuity, filtration and a polytropic curve, J. Pawiński obtains the aforementioned equation of the methane release rate. The identical equation was obtained by J. Roszkowski in his publication (1968) by means of the approximation of the numerical solution of the methane filtration equation. The approximation of the methane release from unmined coal by exponential functions is also used. This form of methane release is presented by J. Roszkowski in (1969) and F.S. Klebanow in (1974).

$$g(t) = g_0 e^{-nt} \tag{8}$$

On the basis of experimental data, Klebanow calculated n that the mean coefficient for the period of several months is 0.023–0.025 $\frac{1}{\text{day}}$, whereas for the time range up to 10 days this coefficient is significantly higher and amounts to $0.175 \div 0.2 \frac{1}{\text{day}}$.

These relationships describe the changes in the methane release rate for times longer than one month well. However, for shorter times some deviations from the predictions described by these formulae are observed.

As mentioned above, B. Kozłowski concludes that in the first month a steady release from unmined coal is observed. In the publication (Tarasow, Kolmakow 1978) its authors introduce the following equation of gas release from unmined coal

$$g = \frac{G_0(t)}{\sqrt{1+t}} \tag{9}$$

and present diagrams of changes in the initial gas release rate $G_0(t)$ in the function of time, calculated on the basis of experimental data for various coal seams in several mines. All diagrams of the function $G_0(t)$ achieve their maximum value in the time range between 7 and 17 h. The authors explain this phenomenon as follows: During the period of formation of the stress relief zone the gas pressure in each section of seam falls and the permeability in points corresponding to these sections rises. Consequently, the initial gas release rate from the seam increases. This rate attains its highest value at the end of the formation of the stress relief zone. Afterwards, permeability stabilises but the gas pressure still falls, which results in a decreased gas release rate. It can be expected that, particularly during the formation of the destruction zone after a collapse, the variability of the initial methane release rate will be considerable.

3.2.2. Gas flow in the porous medium

The gas pressure in coal seams and accompanying rock layers and its changes in time and space are one of the basic factors affecting gas release. The disturbed balance between methane and coal results in some methane contained in the rock desorbing, becoming non-attached and then releases from entering the working from pores and cracks. This gas migration in coal seams and inter-seam layers takes place by means of methane diffusion in ultrapores, micropores and channel-pores, laminar filtration in submicropores and micropores, laminar and turbulent filtration in visible pores and crevices and the movement of methane within the coal-mass. Therefore, the gas movement in coal seams is much different than the viscous isothermal flow described by Darcy's Law.

In literature there are many formulae that describe the movement of sorbed gas in a porous medium.

T. Ryncarz in (1993), assuming that the filtration rate is described by Darcy's Law:

$$v_f = -\frac{k}{\mu}\mathrm{grad}p \tag{10}$$

where:

- k — permeability coefficient,
- μ — gas dynamic viscosity,
- p — gas pressure,

resulting in the following equation of the isothermal filtration gas flow:

$$\frac{\partial p}{\partial t} - \frac{k}{2m\mu}\nabla^2(p^2) = \frac{\beta}{m}\frac{\partial C}{\partial t} \tag{11}$$

where:

- $\beta = \frac{p}{\rho}$
- ρ — gas density,
- m — porosity,

and C is the mass of gas sorbed in a coal or rock volume unit described by Langmuire's isotherm:

$$C = \frac{(1-m)abp}{1+bp} \tag{12}$$

where:

- a, b — sorption constants.

B.T. Tarasow and W.A. Kolmakow (1978) present the gas filtration flow equation in a slightly more general form:

$$k\nabla^2 p^2 + \nabla k \cdot \nabla p^2 = 2RT\mu\frac{\partial}{\partial t}(M_1 - M_2) \tag{13}$$

The mass of free methane in a rock volume unit is as follows:

$$M_1 = \frac{pm}{RT} \tag{14}$$

where:

p — gas pressure,
m — porosity,
R — gas constant,
T — temperature.

The mass of gas sorbed in a volume unit is as follows:

$$M_2 = \frac{abp}{1+bp} \tag{15}$$

where:

$a,\ b$ — Langmuire constant isotherms.

Further, the authors (Tarasow, Kolmakow 1978) assume that the permeability coefficient is a function of gas pressure and introduce the function of the mass filtration rate potential calculated as:

$$F(p) = \frac{1}{\mu}\int k(p)\rho(p)dp \tag{16}$$

By introducing this function to the filtration transport equation in the following form:

$$\nabla\left(\rho\frac{k}{\mu}\nabla p\right) = \frac{\partial}{\partial t}\left(\frac{pm}{RT} + \frac{abp}{1+bp}\right) \tag{17}$$

they obtain:

$$\nabla^2 F(p) = \rho\frac{dm}{dt} + \frac{\rho}{p}\left[m + \frac{RTab}{(1+bp)^2}\right]\frac{\partial p}{\partial t} \tag{18}$$

Then, disregarding $\rho\frac{\partial m}{\partial t}$ on the right side of this equation, and introducing the following symbol:

$$\frac{1}{a} = \frac{1}{kp}\left[m + \frac{RTab}{(1+bp)^2}\right] \tag{19}$$

they obtain equation (18) in the following form:

$$a\nabla^2 F = \frac{\partial}{\partial t}F \tag{20}$$

For boundary and initial conditions it is as follows:

$$F(x,y,z,t)\big|_{t=0} = F_0 \tag{21}$$
$$F(0,y,z,t) = F(x,0,z,t) = F(x,y,0,t) = F_1$$
$$\left.\frac{dF}{dx}\right|_{x\to\infty} = \left.\frac{dF}{dy}\right|_{y\to\infty} = \left.\frac{dF}{dz}\right|_{z\to\infty} = 0$$

The general solution of the equation (20) is as follows:

$$\frac{F(x,y,z,t)-F_1}{F_0-F_1} = \phi\left(\frac{x}{2\sqrt{at}}\right)\phi\left(\frac{y}{2\sqrt{at}}\right)\phi\left(\frac{z}{2\sqrt{at}}\right) \tag{22}$$

where:

$\varphi(\xi)$ is the Gauss probability integral.

$$\phi(\xi) = \frac{2}{\sqrt{\pi}}\int_0^{\xi} e^{-\lambda^2}\,d\lambda \tag{23}$$

Given that the stream of gas mass flowing through the surface S, with the assumption of the filtration flow according to Darcy's Law, is as follows:

$$Q_m = \iint_S \frac{kS}{\mu}\frac{\partial p}{\partial n}\,dS \tag{24}$$

where:

n is the normal to an element of dS surface,

and taking into account the relationship (16), the following is obtained:

$$Q_m = \iint_S \frac{\partial F}{\partial n}\,dS \tag{25}$$

For the one-dimensional flow through a unit surface of open unmined coal perpendicular to the flow direction, an equation of gas mass stream density can be calculated:

$$G_m = \left.\frac{\partial F(x,t)}{\partial x}\right|_{x=0} \tag{26}$$

The equation (22) indicates that:

$$F(x,t) = F_1 + (F_0 - F_1)\phi\left(\frac{x}{2\sqrt{at}}\right) \tag{27}$$

hence, assuming that the initial value G_m corresponds to $t = 1$, the gas mass stream density can be described as follows:

$$G_m = \frac{F_0 - F_1}{\sqrt{\pi a}} \cdot \frac{1}{\sqrt{1+t}} \tag{28}$$

and the gas volume stream density, i.e. the gas release rate:

$$G_v = \frac{G_m}{\rho(p_1)} \tag{29}$$

where:

$\rho(p_1)$ — gas density on the open surface of unmined coal.

The value is calculated from the definition of the function (16).

$$F_0 - F_1 = \frac{1}{\mu} \int_{p_1}^{p_0} k\rho dp = \frac{1}{\mu RT} \int_{p_1}^{p_0} k\rho dp \tag{30}$$

Furthermore, it is assumed that $p_0 = p_L$ is the gas pressure at the border of the stress relief zone of depth L, p_1 is the pressure at the open surface of the unmined coal and that the permeability coefficient is the following function of gas pressure p:

$$k(p) = a_k e^{-b_k p} \tag{31}$$

where coefficient b_k is described by boundary conditions:

$$b_k = \frac{\ln \frac{k_1}{k_L}}{p_L - p_1} \tag{32}$$

After introducing the relationship (31) to (30) and integrating by parts, the result presented in (Tarasow, Kolmakow 1978) is obtained as follows:

$$F_L - F_1 = \frac{p_L - p_1}{\mu RT(\ln k_1 - \ln k_L)} \left[k_1 p_1 - k_L p_L + \frac{(p_L - p_1)(k_1 - k_L)}{\ln k_1 - \ln k_L} \right] \tag{33}$$

Values of the coefficient a (Tarasow, Kolmakow 1978) are as follows:

$$\frac{1}{a} = \frac{\mu}{k_L p_L} \left[m_L + \frac{a_0 b_0 RT}{(1 + a_0 p_L)^2} \right] \tag{34}$$

In these equations k_1, m_1, p_1 are values of coefficients of permeability, porosity and gas pressure on the open surface of unmined coal respectively, whereas k_L, m_L, p_L are these values at the border of the stress relief zone of the depth L. It should be noted that this depth changes with time.

The authors (Tarasow, Kolmakow 1978) present the following relationships for the depth of stress relief, permeability, porosity and gas pressure:

- depth of the stress relief zone:

$$L = L_1 + d(1 - e^{-\alpha t}) \tag{35}$$

where:

L_1 — initial depth of the stress relief zone,
$L_1 + d$ — final depth of the stress relief zone,
α — rheological coefficient,
t — time;

- porosity coefficient:

$$m(x,t) = m_0 + 2\beta U_{\max}\left(1 + \frac{\alpha}{\theta} - e^{-\alpha t}\right)e^{-\beta x} \tag{36}$$

where:

m_0 — filtration porosity of the untouched seam,
β — coefficient depending on geological and operational conditions and coal properties in a seam,
$U_{\max}$ — maximum roof movement above the working,
α, θ — rheological coefficients;

- permeability coefficient:

$$k(x) = a_k m(x) e^{-b_k p(x)} \tag{37}$$

where:

$m(x)$, $p(x)$— porosity and pressure at the distance of x from the open surface of unmined coal,
a_k , b_k — constants calculated on the basis of boundary values: k_0 , k_1 , m_0 , m_1 , p_0 , p_1;

- gas pressure at the border of the stress relief zone

$$p_L = 0.606 p_1 + 0.394 p_0 \tag{38}$$

where:

p_0 , p_1 — gas pressure in the untouched seam and on the open surface of unmined coal.

As indicated in relationships given in the formula that describes changes in the methane release rate:

$$G_v = \frac{G_{v_0}}{\sqrt{1+t}} \tag{39}$$

the so-called initial methane release rate is also a function of time. This function achieves its maximum value at the moment of completion of the formation of the stress relief zone t_{st}

$$t_{st} = \frac{1}{\alpha} \ln \frac{d}{\varepsilon} \tag{40}$$

where ε is the accuracy with which the value of the depth of the stress relief zone in the rheological process is calculated and usually assumed to be $\varepsilon = 0.1$, while d and α as for the relationship (35).

On this basis, and using also results of experimental research of changes in the gas release rate during the formation of the stress relief zone and presented in (Tarasow, Kolmakow 1978), these changes can be described as follows:

$$G_v(t) = \frac{G_{v_0}}{\sqrt{1+t}} \tag{41}$$

$$G_{v_0}(t) = G_{v_0}[1 + g(1 - e^{-\alpha t})] \tag{42}$$

where:

α — rheological coefficient, as in (35) and (36).

4. Methane inflow stream

The methane inflow volume stream q_m can be calculated with the use of formulae (4), (41) specified in Section 3. Two sources of methane inflow from coal fragments and newly created sidewalls were identified.

The inflow from crumbled coal specified by formula (4) is related to the coal mass unit, whereas the inflow from sidewalls is related to the surface unit. After converting into the volume stream related to the working length unit, the total methane inflow is as follows:

$$q_m = (1 - m)\rho_w G_g(t) + UG_v(t) \tag{43}$$

where:

m — porosity coefficient of a section of the working filled with coal chunks after a collapse,
ρ_w — mean coal density (of fragments),
U — length of this part of the working circuit after a collapse, where methane is released,
q_m — methane volume stream flowing to the working per unit length,
G_g — methane volume stream from a mass unit of coal damaged and moved into the working,
G_v — methane volume stream from a surface unit of the working sidewalls.

5. Summary

As a result of this work, a new mathematical model of methane emission to workings after occurrence of a collapse of the rock mass was developed. This model includes:

- inflow of methane from crumbled coal,
- inflow of methane from the stress relieved zone,
- change in parameters of porosity and permeability during the formation of the stress relieved zone.

The model of methane emission presented and the development of the mathematical model of the air and methane mixture distribution disturbed by a tremor or collapse of the rock mass will allow for the development of professional simulation software of the phenomena discussed. It will enable its use to forecast air and methane distribution in emergency conditions after a collapse, which will encompass:

- identification of the zone with risks of elevated methane concentrations,
- identification of the zone characterised by low methane concentration,
- identification of places where additional methane sensors should be installed,
- an analysis of many variants of the ventilation system for mining under conditions of combined dangers,
- reconstruction of the ventilation process after the occurrence of a disturbance.

Such forecasting will enable correct conclusions to be arrived at and for evaluative steps to be taken during real rescue operations involving saving human lives and gas removal in a mine.

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