Mathematical modeling of methane migration into the mine workings during the face downtime

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Abstract. For the estimation of safe distances during explosions of mixtures of coal dust, methane, and air in the process of emergency rescue operations in coal mines, it is necessary to determine the gas volumes in the mine workings. Errors in determining such volumes often lead to tragic consequences. The calculation schemes are suggested that allow the methane generation rate into the mine air to be determined on the basis of physical regularities (mine and gas pressures, gas permeability dynamics, depth of the gas drainage zone, etc.), underlying the processes of gas migration from coal and rocks into the mine workings. The following methane emission sources are considered at the site: the surface of the stopped face; walls of development opening; the gob (potential volume of the gas reservoir in the caving area). Test calculations of methane generation have been performed based on the mining, geological and technological data of one of the mines in Baydaevsky geological and economic region. In general, the results obtained are consistent with the data of long-term empirical observations. The directions of further research aimed at improving the synthesized methodology are presented.

1. Introduction

In the course of conducting mine rescue operations in mines, there is a need to determine the safe distances during explosions of coal dust methane-air mixtures. To do this, the specialized software products are used, which require the gas volume in the workings to be specified as initial data. The definition of such volumes during mine rescue operations, as well as during face standbys, depends on many factors: mining and geological parameters of the seams; schemes of opening and preparation of a mine field; mining technology; type and place of the accident, etc. Methods of their determination are very different and depend on the specific conditions. Errors in the definition lead to tragic consequences.

To estimate the gas volumes in the workings, the calculation of the total methane generation for a certain period of time is necessary. The calculation schemes given in the current normative and technical documents on design of ventilation in mines and working areas are based on the estimation of relative gas content by difference between the natural and residual gas content, as well as on the data about the actual methane release obtained during development of extraction pillar by longwalls-analogs. Absolute methane content in these cases is determined only depending on the planned daily load on the face and the speed of excavation, i.e. in the conditions of normal operation of the mining enterprise. In addition, the physical laws that underlie the processes of gas transfer from coal to mining are not taken into account. In connection with this the actual task is to develop methods for estimation of the absolute methane content in the working area and its dynamics during emergency stops of faces. The performance of numerical modeling of geomechanical processes raises the accuracy of the estimate of absolute methane content in the working area [1 - 7].

Methane generation rate from satellite strata, coal loss and from the coal that can be located on the transport chain of the site is not considered due to certain difficulties in its determination. Further, the calculations are made for the conditions of the working area of one of the mines in Baydaevsky geological and economic region.

During emergency stops the following sources of methane emissions in the area are proposed to consider: the gob (potential volume of the gas reservoir); surface of the stopped face; walls of the prepared workings.

2. Methods of research

Assessment of the methane yield from free faces

To estimate the methane yield from all seam exposed surfaces, according to our understanding of the problem the mathematical model of B.G. Tarasova – V.A. Kolmakova is preferred [8 - 10]. It allows the change of gas content in time, depending on the rock and gas pressures to be taken into account, as well as gas permeability of the massif.

This model is based on the potential function of L.S. Leybenzon $F(H)$, which takes into account the conditions of gas filtration depending on the massif permeability $k(H)$, medium density $\rho(H)$, gas pressure and the depth of operations carried out H.

$$F(H) = \frac{1}{\mu}\int k(H)\rho(H)dH, \tag{1}$$

where μ – Dynamic viscosity of methane, kgf·s/m^2.

The magnitude and nature of gas release from the massif are determined by the following parameters: the mass velocity potential or a complex of variable magnitudes reflecting the state of the massif and gas (gas pressure, permeability, porosity, density and gas viscosity); speed of the face advance; intensity of the internal source of gas release; state of the gas bearing medium.

Mathematical model – differential equation of gas motion in an massif, containing an internal source of gas release, has the following form

$$C_1(x_i,t)\frac{\partial F}{\partial t} = \sum_{i=1}^{3}\left\{\frac{\partial}{\partial x_i}\left[a(x_i,t)\frac{\partial F}{\partial x_i}\right]\right\} + \sum_{i=1}^{3}\left\{v_{\mathrm{f}}(x_i,t)\frac{\partial F}{\partial x_i}\right\} - B(x_i,t)F + q(x_i,t), \tag{2}$$

where x_i – the distance into the depth of the massif; t – time; a – coefficient that takes into account free and sorbed gas; v_{f} – rate of face advance; q – intensity of the internal source of methane emission; C_1, B – coefficients.

Depending on the values of parameters, equation (2) can be applied to various special cases. With $C_1 = 1$ $v_{\mathrm{f}} = 0$, $B = 0$, $q \neq 0$ it allows us to calculate it from the coal massif with the stopped face.

To estimate the gas emissions from the developed seam, it is also necessary to estimate the change in depth of unloading zones $l(t)_i$, m, and gas drainage $l_{\mathrm{dr}.i}$, m, due to the influence of mining operations [8, 10]. The dynamics calculation of the unloading zone depth takes into account the changes in the rheological properties of the massif over time (figure 1), which are estimated by the coefficient $k_{t.i}$ according to the formulas:

- for the face

$$k_{t.i} = -\frac{\alpha_{\mathrm{r}}(t_0 + t_i)}{1440}, \tag{3}$$

- for development workings

$$k_{t.i} = -\alpha_{\mathrm{r}}\left(\frac{1}{2}t_{\mathrm{b}} + t_{\mathrm{sh}} + \frac{t_0 + t_i}{1440}\right), \tag{4}$$

α_r – rheological coefficient; t_b – time from beginning of tunneling up to its end, days; t_{sh} – time elapsed between the moment of finishing the development working and the face shutdown, days; t_0 – time elapsed between the moment of seam exposure (face shutdown) and the moment of emergency, min; t_i – time elapsed from the moment of emergency (value t_i changes to t_n), min.

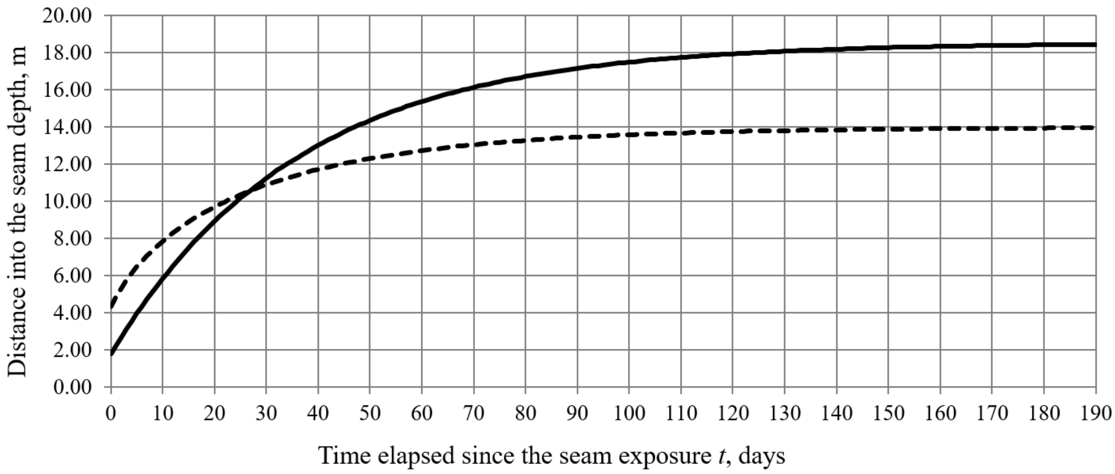

Figure1. Dynamics of the unloading zone depth $l(t)_i$ (dashed line) and gas drainage $l_{dr.i}$ (solid line) of the seam for the period from $t_0 = 0$ to t_{st} (time of stabilization of stress-strain state).

To calculate the gas emission from the seam, it is necessary to determine the initial gas pressure and the regularity of its change under the influence of mining operations. Based on the assumption that the unmined coal-bearing strata is a gas reservoir of free methane, the depth pressure P_0, kgf/cm^2, is distributed according to hydrostatic dependence [8, 10]

$$P_0 = u(H - H_0)^v + P_2, \tag{5}$$

where u, v – empirical coefficients reflecting the influence of natural factors such as gas permeability of coal and rocks, angle of strata inclination; H, H_0 – depth, respectively, of mining works and the zone of degassing, m; P_2 – gas pressure at the upper boundary of the methane zone, kgf/cm^2.

With approximate calculations the gas pressure in the unmined massif P_0, kgf/cm^2, can be estimated from the general formula [11]

$$P_0 = 0.1(H - H_0). \tag{6}$$

The gas pressure at any distance deep into the seam P_x, kgf/cm^2, at each moment of time t ($0 \leq t \leq t_{st}$) from its detection and to stabilization of the stress-strain state is calculated by the formula

$$P_x = (P_1 - P_0)e^{-\frac{x^2}{2l^2(t)}} + P_0, \tag{7}$$

where P_1 – gas pressure on the drain surface, kgs/cm^2 (due to incomparability of gas pressures in the mine working and in the massif, it is assumed that at the drain boundary the pressure equals to atmospheric pressure $P_1 = P_{atm} = 1$ kgf/cm^2); P_0 – gas pressure in the unmined massif, kgf/cm^2; x – distance deep into the massif, m.

The specific gas release from the unit area of the seam immovable surface during the formation of unloading zone $G_{t.i}$, m^3/(m^2·min), is determined by formulas [8-10]:

- for stoping

$$G_{t.i} = \frac{G_0}{\sqrt{\frac{t_0+t_i}{1440}+1}}; \quad (8)$$

- for development workings

$$G_{t.i} = \frac{G_0}{\sqrt{\frac{1}{2}t_{\text{пр}} + t_{\text{ост}} + \frac{t_0+t_i}{1440}+1}}. \quad (9)$$

where G_0 – initial gas release intensity G_0, m3/(m2·min), at the time of seam exposure, is determined depending on the difference in potential functions of gas release $\left(F_{l(t)} - F_1\right)_{\text{s}}$.

Gas evolution in the face, taking into account the drainage effect of the development workings $I_{\text{f}.i}$, m^3/min, at the moment of time $t_0 + t_i$, min, is determined by the formula

$$I_{\text{f}.i} = G_{t.i} m_{\text{m}} \left[l_{\text{f}} - \frac{1}{2}\left(l_{\text{dr}}^{\text{c}} + l_{\text{dr}}^{\text{v}}\right) \right], \quad (10)$$

where m_{m} – mined thickness of a seam, m; l_{f} – face length, m; $l_{\text{dr}}^{\text{c}}, l_{\text{dr}}^{\text{v}}$ – depths of the zone of seam drainage, respectively, by conveyor and ventilation drifts, m.

Gas release into the development working from the seam $I_{\text{d.w.}}$, m^3/min, at the moment of time $t_0 + t_i$, is determined by the formula

$$I_{\text{d.w.}i} = 2G_{t.\text{d.w.}i} a_{\text{ex}} l_{\text{d.w.}}, \quad (11)$$

where $G_{t.\text{d.w.}i}$ – specific gas release from a unit of the area of the immovable seam surface in the development workings, m^3/(m^2·min); a_{ex} – seam exposure, m; $l_{\text{d.w.}}$ – length of the development working, m.

Figure 2 gives an example of calculation of gas release from the exposed seam surface (face). The step of calculation corresponds to days.

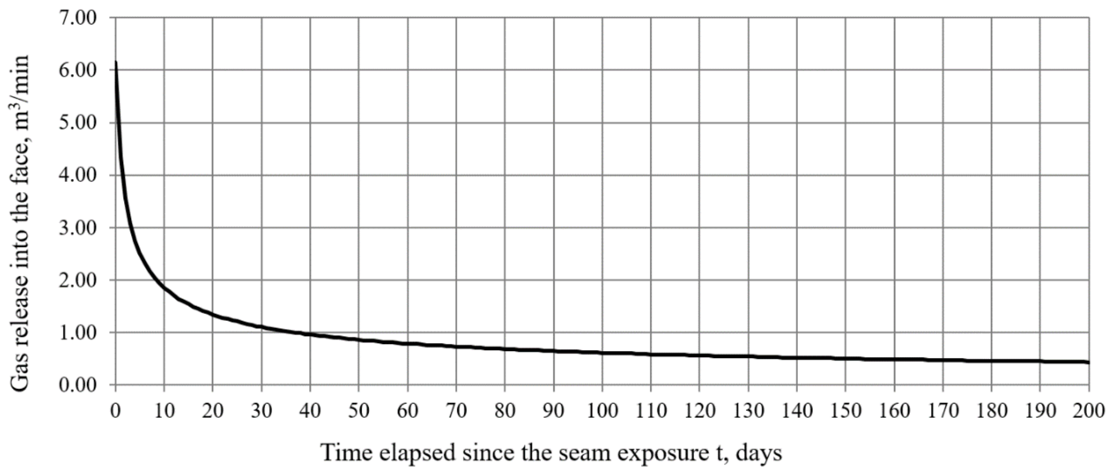

Figure 2. Dynamics of change in methane generation rate from the developed seam (face) during the period from $\boldsymbol{t_0 = 0}$ till $\boldsymbol{t_{\text{st}}}$.

Estimation of the volume of gas reservoir in the caving zone

The gob is an active component of aerogasdynamic system of working areas characterized as a medium with high aerodynamic permeability (by 2-4 times higher than in the unmined massif) [1, 2]. In the dome of caving and areas not ventilated by air leaks, as a result of gas mixture release from the coal-bearing seam its considerable volumes can be accumulated – a gas reservoir is formed. In the certain conditions the gas mixture can be squeezed into the workings. In this regard, it is necessary to evaluate the possible volumes of the gas reservoir.

To determine the formed volumes in the gob of the gas reservoir and determine the magnitude of free lowering of the main roof rocks h_{fr}, m, it is necessary to estimate the rocks fragmentation during caving. For shallow seams, the maximum fragmentation index $k_{\mathrm{frag.max}}$ can be found from table 1.

Table 1. Maximum $k_{\mathrm{frag.max}}$ for roof caving [2].

Seam thickness, m	Values $k_{\mathrm{frag.max}}$
from 1.2 to 2.0	1.8
from 2.0 to 3.0	2.0
from 3.0 to 3.5 and more	2.1

As a criterion for determining the boundary between the caving zone and the zone of cracks and faults, a fragmentation index 1.1 is chosen. With a smooth reduction of k_{frag} with a decrease in the caving height of the next sublayer, it can be calculated from the linear dependence (table 2).

Table 2. Distribution of k_{frag} in the caving zone [2].

Relation of a free space to the thickness of a caved layer $h_i/m_{\mathrm{c.l.}}$*	Value of k_{frag}		
	$k_{\mathrm{frag.max}} = 1.80$	$k_{\mathrm{frag.max}} = 2.00$	$k_{\mathrm{frag.max}} = 2.10$
2.30 and more	1.80	2.00	2.10
from 1.50 to 2.29	1.65	1.80	1.90
from 0.75 to 1.49	1.40	1.50	1.50
from 0.50 to 0.74	1.20	1.30	1.30
from 0.20 to 0.49	1.15	1.15	1.20
to 0.19	1.10	1.10	1.10

*$m_{\mathrm{c.l.}}$ – thickness of the caved sublayer of the immediate roof, m; h_i – free space after caving of the next sublayer, m.

Free space after caving of sublayers of immediate roof rocks h_i, m, can be determined by the formula

$$h_i = h_{i-1} - m_{\mathrm{c.l.}i}(k_{\mathrm{l}.i} - 1), \tag{12}$$

where h_{i-1} – free space remained after the caving of the previous layer, m, for the first sublayer is assumed equal to the extracted seam thickness; $m_{\mathrm{c.l.}i}$ – thickness of the caved sublayer (chosen according to the frequency of cracks in the roof rocks), m; $k_{\mathrm{l}.i}$ – coefficient of loosening for the caving sublayer.

Calculation of free space is performed before the layer of rock-bridge. If this layer turned out to be cleavaged, the crash of its consoles will take place without any dynamic phenomena. If the height h_i (h_{fr}) is not equal to zero, during caving of the rock-bridge layer gas can be transferred to the working site from the gas reservoir. In this case, its volume $V_{\mathrm{g}.r.}$, m^3, can approximately be estimated by formula

$$V_{\mathrm{g.c.}} = 0.5 h_{\mathrm{fr}} l_{\mathrm{w}} l_{\mathrm{f}}, \tag{13}$$

where l_w – face withdrawal since the last caving of the rock-bridge, m; l_f – длина очистного забоя, м. length of the face, m.

3. Results and discussion

According to the methods for estimating the volume of methane release from the developed seam and the potential volume of the gas reservoir a test calculation was performed (the scheme of the working area for which the calculation is performed is shown in figure 3):

- time elapsed since the disturbance of airing $t_i = 97$ min;
- the volume of methane released in:
  - face $V_{f.} = 572$ m^3;
  - belt road $V_{b.r.} = 506$ m^3;
  - wind roadway $V_{w.r.} = 631$ m^3;
- approximate volume of the gas reservoir (it is assumed that the length of the suspended console is close to the caving step) $V_{g.c.} = 518$ m^3.

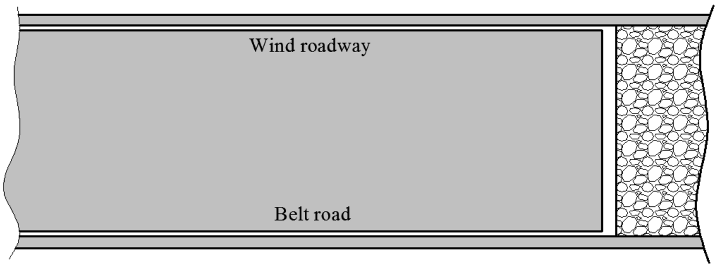

Figure 3. Scheme of the working area for which the test calculation was performed.

Currently, work is being done in order to improve this methodology, including the accounting of methane-air mixtures filtration in the gob. The method is being developed on the basis of account of interacting geomechanical and gas dynamic processes during mining operations for specific mining, geological and technological conditions (figure 4). The planned final result is a problem-oriented software package that allows to quickly the tasks in the field of gas dynamics to be solved quickly.

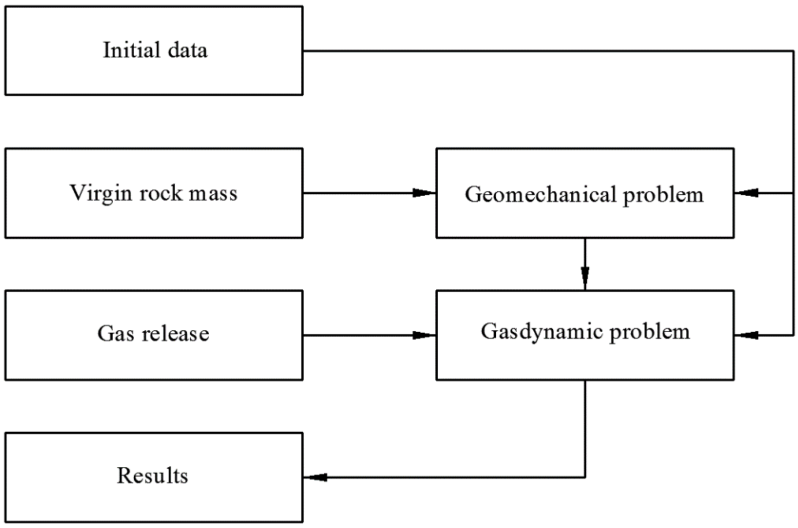

Figure 4. Conceptual scheme for solving the problem of modeling the gas release processes into the mine workings.

4. Conclusion

The results of the research presented in this paper are only a part of a very complex gas-dynamical problem. For further work, the main tasks are determination of gob and seam permeability, as well as the initial gas pressure in the massif. In general, the results of the studies (figure 2, 3) correspond to the data of long-term empirical observations. The developed technique allows the volumes of released methane for any time interval to be determined taking into account the depletion of sources and potential volumes of gas reservoir. The implementation of the results will increase the calculation accuracy of gas volumes in the mine workings and will contribute to the safe performance of mine rescue works.

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