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Spatiotemporal distribution of methane concentration from broken coal mass

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Abstract. The paper proposes a mathematical model, based on a one-dimensional nonhomogeneous diffusion equation, which enables the evaluation of methane emissions from extracted coal during its transportation through the haulage system of a coal mine longwall face and their contribution to spatiotemporal distribution patterns of mine atmospheric parameters characterizing the gas environment in the face area. The solution to the specified equation has been implemented using the Mathcad computational software package. The results of numerical experiments demonstrate potential applicability for enhancing operational efficiency in managing technological processes within the boundaries of the longwall face.

1 Introduction

At present, due to the implementation of effective ventilation and degasification schemes at coal mining enterprises, as well as the introduction of modern gas monitoring systems, the probability of catastrophic accidents caused by methane factors continues to steadily decrease [1]. However, situations where mine atmospheric parameters in mine workings approach maximum regulatory limits defining gas contamination in the face area and surrounding extraction workings, leading to stoppage of technological equipment, remain a significant cause of reduced productivity in coal mines [2]. Therefore, maintaining the rhythm of technological processes in coal mines requires priority development of systems for operational control of mine atmosphere parameters within extraction areas. The effective functioning of such systems depends both on timely identification of methane emission sources that have the most significant impact on the gas balance of extraction areas, and on unambiguous mathematical description of developing aerological situations [3].

It is known that methane emission intensity in longwall faces increases with higher advance rates of shearer, with the main gas inflow into working faces and haulage openings being primarily provided by broken coal [4,5].

Therefore, the objective of this study is to develop a mathematical model for evaluating the contribution of methane release from broken coal during its transportation through the

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haulage system of a mine extraction area to the spatiotemporal distribution of parameters characterizing the state of mine atmosphere in the face zone.

2 Materials and methods

In the considered mining system, the longwall face length *L* is set to 350 m, with a cross-sectional area $S \approx 5$ m². The shearer speed *V* is 0.1 m/s, and the uniform speed of the scraper conveyor *U* is 1.3 m/s. The primary source of methane entering the face area is assumed to be gas emission from pieces of broken coal uniformly distributed along the conveyor. The intensity of methane emission from the extracted coal is considered constant over time [5]. Furthermore, the influence of ventilation in the described extraction area is excluded from the modeling process.

Since the longwall face length significantly exceeds its height and width, the main equation describing methane propagation in the longwall face is taken as the one-dimensional inhomogeneous diffusion equation [6]:

$$n_t' - a^2 n_{xx}'' = f(x,t) \tag{1}$$

Here *n(x, t)* represents the concentration of methane in the air. To solve this equation, we employ the Green's function (source function) apparatus. The influence of a point and instantaneous source of gas emission, acting at point ξ at time τ, is described by the Green's function [6]:

$$G(x,t,\xi,\tau) = \frac{1}{2\sqrt{\pi}a\sqrt{t-\tau}} e^{-\frac{(x-\xi)^2}{4a^2(t-\tau)}} \tag{2}$$

Then, if the gas source has an intensity *f(x, t)*, the methane concentration *n(x, t)* due to diffusion is given by the expression.

$$n(x,t) = \int_0^t d\tau \int_{-\infty}^{+\infty} d\xi f(\xi,\tau) \cdot G(x,t,\xi,\tau) = \int_0^t d\tau \frac{1}{2\sqrt{\pi}a\sqrt{t-\tau}} \int_{-\infty}^{+\infty} d\xi f(\xi,\tau) \cdot e^{-\frac{(x-\xi)^2}{4a^2(t-\tau)}} \tag{3}$$

where *a* is a parameter characterizing the intensity of the diffusion process. In practice, the diffusion coefficient $D = a^2$, with dimensions m²/s, is typically used [2,6]. The variables *x* and *t* describe the spatial and temporal coordinates of the point at which the gas concentration needs to be determined, while the variables ξ and τ define the location of the source.

Fig. 1. Calculation scheme for the movement of broken coal along the transport system of the mining area.

If the longwall shearer moves uniformly at velocity *V*, and the scraper conveyor moves at velocity *U* in the opposite direction, then the conveyor is uniformly filled with broken coal over the segment from the initial point 0 to *V·t* (figure 1). At each point of the specified segment, the methane concentration *n(x, t)*, recorded at time *t*, is determined by the gas emission sources (pieces of broken coal) that fall onto the conveyor from the time *x / V* until time *t*. Consequently, we can write:

$$n(x,t) = \int_0^{vt} d\xi \int_{\frac{x}{v}}^{t} d\tau \frac{1}{2\sqrt{\pi}a\sqrt{t-\tau}} f(\xi,\tau) \cdot e^{-\frac{(x-\xi)^2}{4a^2(t-\tau)}} \tag{4}$$

Let us make another significant assumption. Evidently, if *P* [kg/s] is the productivity of the shearer, then during time *Δt*, coal with mass *ΔM=P·Δt* is extracted. Note that the conveyor speed relative to the shearer is *U* + *V*. Thus, during time *Δt*, a conveyor length of *ΔL=(U+V)·Δt* passes by the shearer, meaning the linear density of coal on the conveyor is ρ_n = *ΔM/ ΔL= P/(U+V) = const*. If we assume that methane emission from a unit mass of extracted coal does not significantly change during the time it takes for a piece of broken coal to move a distance equal to the face length L (approximately 5 minutes in the case under consideration) [5], then we can consider that the methane emission intensity *f(x, t)* for coal on the conveyor depends neither on coordinate nor time and can be replaced by a constant f_0.

For a quantitative assessment of the constant f_0, let us calculate the methane emission intensity from a unit mass of broken coal per unit time *N*. Assuming the methane content of coal $X = 5\ m^3/t$, and considering that the time of most intensive methane release from extracted coal is Δt = 20 min, with methane density ρ_m = 0.657 kg/m^3, we obtain $N = \rho_m \cdot (X/t)$ = 2.74·10-3 g/(kg·s). Consequently, the methane emission intensity from an element of conveyor length is $N_{\Delta L} = N \cdot \Delta M = P \cdot N \cdot \Delta L/(U+V)$. Considering that in reality, the methane mass ΔM is distributed over volume $\Delta V = S \cdot \Delta L$, where *S* is the cross-sectional area of the excavation, we obtain that the calculated value of the constant $f_0 = P \cdot N/S \cdot (U+V)$ = 7.7 g/(m^3·s).

In the expression for *n(x, t)*, it is convenient to change the order of integration. For this purpose, let us depict the integration region on a phase diagram, presented in Figure 2. Here, at each moment of time from 0 to *t*, the broken coal on the conveyor is present on the segment from 0 to point $V \cdot \tau$, where the shearer is located at that moment. Therefore, the spatial coordinate ξ varies from 0 to $V \cdot \tau$, and τ from 0 to *t*.

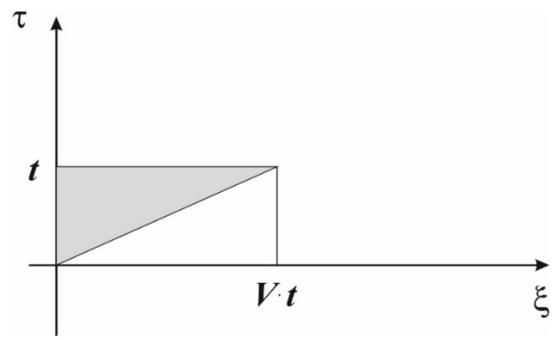

Fig. 2. Phase diagram.

Using the phase diagram, we obtain:

$$n(x,t) = \int_0^t d\tau \frac{1}{2\sqrt{\pi}a\sqrt{t-\tau}} \int_0^{v\tau} d\xi f_0\, e^{-\frac{(x-\xi)^2}{4a^2(t-\tau)}} \quad (5)$$

It is known that changes in the distribution of methane concentration in air are caused not only by diffusion processes, but also by convective flows, which contribute more significantly to the rate of gas propagation in space [7]. Consequently, the actual values of gas propagation velocity in air substantially exceed the values of the same parameter obtained by solving the classical diffusion equation. However, convection caused by the presence of numerous point sources of air movement in the medium can be approximately described by the diffusion equation with a much larger coefficient *D* after averaging. Therefore, calculations to estimate the values of the function *n(x, t)*, using expression (5), were performed with a diffusion coefficient $D = 25 \cdot 10^{-5}$ m^2/s. Figures 3a - 3c show the graphs of *n(x)* dependencies obtained during calculations using formula (5), conducted in the Mathcad software package for three time points t_1 = 200 s, t_2 = 2000 s, and t_3 = 5000 s. The maximum value of *x* on the graphs corresponds to the length of the longwall *L*.

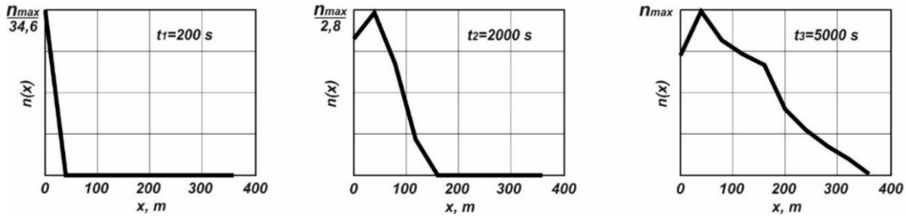

Fig. 3. Graphs of *n(x)* at different moments of time *t*.

In the indicated graphs, n_{max} denotes the maximum value of the function *n(x)* at time t_3, and the upper limits of the vertical axes of the graphs in figures 3a and 3b are equal to the value of n_{max} multiplied by the corresponding proportionality coefficients. The changes in the functional dependencies presented in figures 3a–3c indicate an increase in methane concentration at any selected point in space over time, which is associated with the movement of the shearer and scraper conveyor. It is noteworthy that the maximum methane concentration $n(x)_{max}$ is initially observed at the point corresponding to the initial position of the shearer and slowly shifts to the right over time.

3 Conclusion

In formulating the research problem and conducting further calculations, a number of significant assumptions and limitations were made. However, the graphs of dependencies *n(x)*, obtained during modeling for various time values *t*, can be unambiguously interpreted, and the assessments made based on this regarding the nature of changes in the state of the mine atmosphere correspond to the considered mining engineering and aerological situations. Therefore, the proposed mathematical model, when accounting for the influence of mine ventilation in its computational scheme, can provide reliable estimates of aerological parameters necessary for enhancing the efficiency of operational management of technological processes within the extraction area.

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