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# MATHEMATICAL MODELS OF GAS-DYNAMIC AND THERMOPHYSICAL PROCESSES IN UNDERGROUND COAL MINING AT DIFFERENT STAGES OF MINE DEVELOPMENT

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New trends have been traced and the existing ones refined regarding filtration and diffusive motion of gases in coal beds and surrounding rock, spontaneous heating of coal and transport of gas traces by ventilation currents in operating coal mines. Mathematical models of gas-dynamic and thermophysical processes inside underworked territories after mine abandonment have been justified. Mathematical models are given for feasible air feeding of production and development areas, as well as for the development of geotechnical solutions to ensure gas-dynamic safety at every stage of coal mine operation. It is demonstrated that the use of high-performance equipment in the production and development areas requires more precise filtration equations used when assessing coal mine methane hazard. A mathematical model of pressure field of non-associated methane in the edge area of the coal seam has been justified. The model is based on one-dimensional hyperbolic equation and takes into consideration final rate of pressure distribution in the seam. Trends in gas exchange between mined-out spaces of high methane- and $CO_2$-concentration mines with the earth surface have been refined in order to ensure environmental safety of underworked territories.

***Key words*:** mathematical model, gas-dynamic process, coal seam, mineral rocks, mined-out spaces, methane, oxygen, carbon dioxide, geotechnology

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**Assessment of aerological safety of underground coal mining.** Numerous mines in the Kuznetsky, Vorkuta and Donetsk regions are gas-hazardous and, according to the statistic of methane-air-mixture (MAM) explosions in Russian coal mines, until now there is no effective prevention system for this type of accidents. At the same time the technology «coal mine – longface» is being put to wide use, which implies great production from a longface – up to 20-30 kt/day [2]. Foreign approach to solving problems of mine gas dynamics is very pragmatic – financial considerations integrate the most successful technological solutions into a least expensive system. Nevertheless, it is essential to have scientific justification for these technologies, proving their aerological safety. E.g., at a typical high-production coal mine in the US a 10 % lost work day due to accidents related to gas factor can lead to the losses of 1 million USD, and a single accident inflicts additional harm of 2-8 million USD due to production losses, legal costs, reimbursements and fines [2, 3]. Existing methods of forecasting for gas-dynamic processes define the level of safety of underground coal mining and environmental consequences at each stage of coal mine operation inside mining regions, therefore they require more thorough scientific justification [12, 16].

High methane content of the coal seams is the reason why high-productive technologies of underground coal mining have a gas barrier. However, existing technologies of geoecological survey do not meet criteria of environmental safety for the territories of mining operations and abandoned mines [5, 11]. Hence, complex research on gas dynamics of underground coal mining, defined by geotechnological and geoecological processes, is a very relevant issue.

Intensity of gas emissions from a source is a time-variant [18]. The share of the source in the total balance depends on both its potential gas activity and the time since the source started emitting. The key sources of gas emissions are known, and today there is an extensive factual material on their gas outflow [13]. Gas emissions from a working seam are defined by the intensity of gas recovery from exposed surface and loose coal. Gas emissions from mined-out spaces are composed of gas coming from adjacent seams, under- and overworked beds, as well as emissions from spontaneous caving zones or blind workings, isolated from mined-out spaces with a stopping. Statistical analysis of coal mine accidents shows that the efficiency of existing methods of MAM explosion forecasting, physical model and mathematical description of gas explosion risks in coal mines remain unsatisfactory [9].

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Therefore it is necessary to develop systematic principles to reduce threats of technological accidents in the coal mines, which will be based on aerologic and gas-dynamic risk modeling, as well as on gas situation modeling in case explosion threat signs occur. Analysis of MAM explosion risk structure allows to conceptually express the risk as follows:

MAM explosion risk = Probability of MAM explosion × Damage from the explosion.

When calculating the effectiveness of preventive measures, assessing the risk of accident and designing emergency response plans, consideration should be given to the incident rates and safety indicators of the mine.

Kuznetsk coal basin is regarded as Russia's most promising region. However, not without practical interest are other potentially unprofitable coal basins. Gassy mine workings are not rare in Kuznetsk basin, and gas-hazardous situations occur quite often. Dangerous gas situations are also inherent to the mines with high carbon dioxide ($CO_2$) concentration, being caused by «dead air» emissions. They can be explained by low-temperature coal oxidation in the mined-out space and a drop in atmospheric pressure [4, 6, 8].

Progressive technological schemes of coal extraction and high-performance mining machinery create difficult gas situations in working areas and prevent highest possible capacity from being reached. The cycle of underground coal mining causes various gas-dynamic and thermophysical processes within the bounds of a minefield (Fig.1). Mathematical description of these processes can be carried out using partial differential equations from mathematical physics [10, 17].

**Mathematical models of gas-emission dynamics in high $CO_2$-content mines.** Gas emissions from rock masses and mined-out spaces, containing non-associated gases and unabsorbed gas mixtures, can be expressed in linearized filtration equation. This mathematical model serves as a base for forecasting emergency gas emission, caused by reduced static air pressure in the mine working, i.e. in case atmospheric pressure drops and the main fan is reversed.

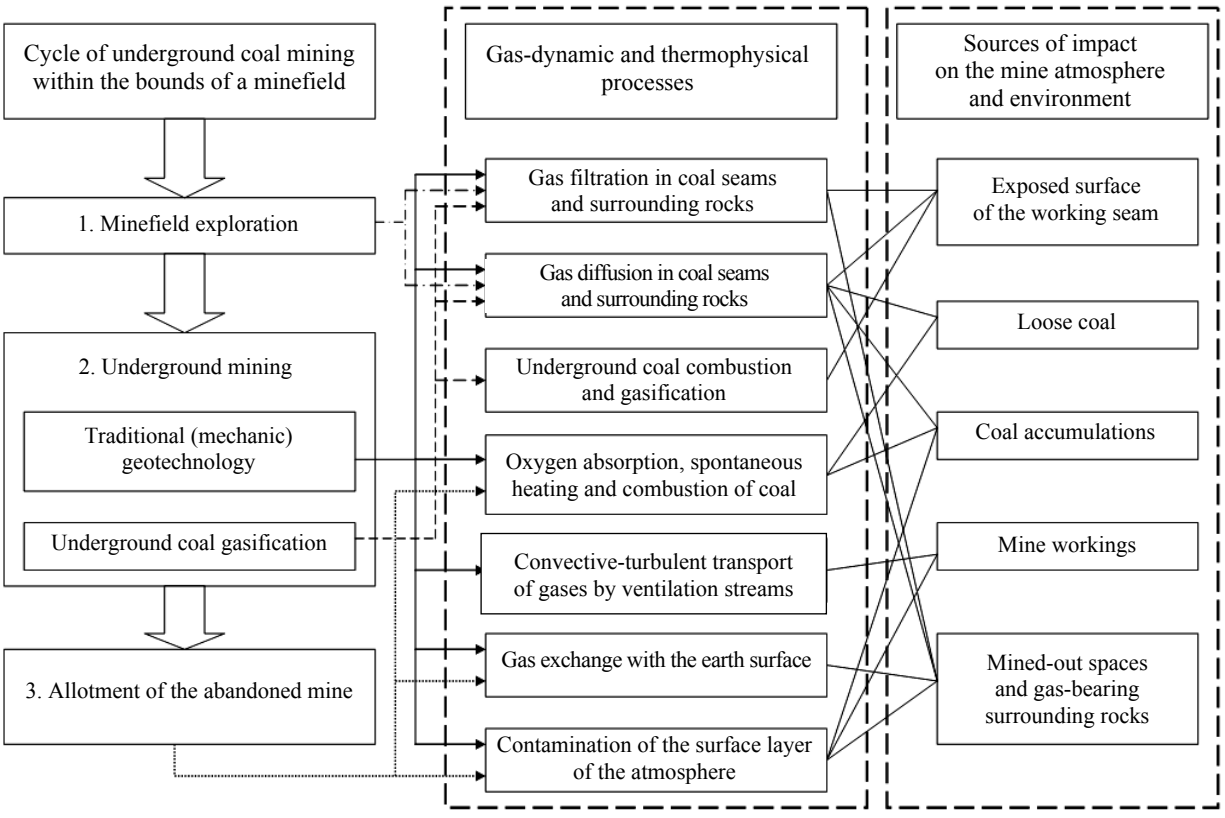



Fig.1. Gas-dynamic and thermophysical processes of underground coal mining geotechnology at different stages of field development

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However, for a long time the limits to applicability of the linearized equation have not been estimated. In order to get these estimations comparisons have been drawn between number value solutions of a non-linear filtration equation and number values obtained through a linearized equation. Results of such simulation experiments make it clear that both L.S. Leibenson's and I.A. Charny's methods give a good fit to the exact solution [4]. The error does not exceed several percents.

Process of gas exchange between the coal seam and the atmosphere in non-gassy mines is determined by oxygen absorption and $CO_2$ emission. The process occurs in terms of Knudsen diffusion. Theoretical relations and formulas for engineering calculations have been obtained. The volume of oxygen passing through a unit of exposed surface in a unit of time is defined as follows:

$$I_{\text{K}} = c_{\text{air}} D_{\text{o}}^{0.5} [(\pi t)^{-0.5} \exp(-K_{\text{O}} t) + K_{\text{O}}^{0.5} \text{erf}(\sqrt{K_{\text{O}} t})], \quad (1)$$

where $c_{\text{air}}$ – oxygen concentration in the air of the mine; $D_{\text{o}}$ – coefficient of oxygen diffusion in the coal; $K_{\text{O}}$ – constant rate of low-temperature coal oxidation.

Analysis of the expression (1) shows that for practical reasons it is feasible to use limit value $I_{k\infty} = \lim\limits_{t\to\infty} I_{\text{K}}$, which can be calculated using formula $I_{k\infty} = c_{\text{в}} \sqrt{D_{\text{o}} K_{\text{O}}}$. Then the rate of $CO_2$ emission caused by the process of low-temperature coal oxidation can be determined from the formula $I_{\text{co}_2}^{\text{s}} = I_{k\infty} K_{\text{r}}$, where $K_{\text{r}}$ – respiratory ratio.

**Mathematical models of gas-emission dynamics in high methane-content mines.** The application of high-performance equipment in production and development areas requires more precise filtration equations used for the assessment of the mine's methane hazardousness. A mathematical model of pressure field of non-associated methane in the edge area of the coal seam has been justified. The model is based on one-dimensional hyperbolic equation and takes into consideration final rate of pressure distribution in the seam. Methane emission from a unit of exposed surface in a working seam is determined from the formula $I_{sc} = I_{\text{in}} \exp(-0.5t/t_r) I_0(0.5t/t_r)$, where $I_{in}$ – initial rate of gas emission; $t_r$ – relaxation period; $I_0(0.5t/t_r)$ – modified 0$^{\text{th}}$-order Bessel function for the argument in brackets.

In order to model dynamics of absolute gas volume in the coal mine the following relations have been established [7,14]: methane emission in the development workings

$$I_{\text{d.w.}}(t) = \begin{cases} 0.318\, n m_{\text{cs}} t_r V_{\text{d.f.}} I_{\text{in}} \Theta_1(\tau) \text{ for } \tau \le \tau_{\text{d.w.}}, \\ I_{\text{d.w.}}^{\max} \Theta_2(\tau - \tau_{\text{d.w.}}) \text{ for } \tau \ge \tau_{\text{d.w.}}; \end{cases} \quad (2)$$

methane emissions in the development face

$$I_{\text{d.f.}}(t) = I_{\text{d.f.}}^{\max} = 0.318\, m_{\text{cs}} t_r V_{\text{d.f.}} I_{\text{in}} \Theta_1(\tau_m), \quad (3)$$

methane emissions in the production face

$$I_{\text{p.f.}}^{\max}(t) = 0.637\, n\, m_{\text{cs}} t_r V_{\text{p.f.}} I_{\text{in}} \Theta_1(\tau_{\text{p.f.}}), \quad (4)$$

where

$$I_{\text{d.w.}}^{\max}(T_{\text{d.w.}}) = 0.318\, n m_{\text{cs}} t_r V_{\text{d.f.}} I_{\text{in}} \Theta_1(\tau_{\text{d.w.}});$$

$$\Theta_1(\xi) = \int_0^{\xi} \exp(-\zeta) \int_0^{\pi} [\exp(\zeta \cos\theta) + \exp(-\zeta \cos\theta)] d\theta d\zeta;$$

$$\Theta_2(\xi) = 0.159 \exp[-(\xi - \tau_{\text{d.w.}})] \int_0^{\pi} \{\exp[(\xi - \tau_{\text{d.w.}})\cos\theta] + \exp[-(\xi - \tau_{\text{d.w.}})\cos\theta]\} d\theta;$$

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$\Theta_1(\xi)$, $\Theta_2(\xi)$ – non-dimensional functions of methane emission; $n$ – number of exposed surfaces of the coal seam; $m_{cs}$ – thickness of the coal seam; $V_{\text{d.f.}}$, $V_{\text{p.f.}}$ – advance rates of development and production faces respectively; $T_{\text{d.w.}}$ – duration of development working construction; $\tau_{\text{d.w.}}$, $\tau_{\text{m}}$, $\tau_{\text{p.f.}}$ – non-dimensional values of development working construction time, maximal digression of the cutter-loader from the timbering and longwall passage by the cutter-loader.

Expressions (2)-(4) allow to forecast the dynamics of methane emissions from exposed surfaces of the working seam. Results of simulation experiments allow to determine the type of functions $\Theta_1(\xi)$ and $\Theta_2(\xi)$. The approximation of functions has been carried out using cubic and square polynomials. Notably, the correlation coefficient of these approximations is close to one.

Maximal value of methane rate from loose coal in case of a development working is calculated as follows: $I_{\text{lc}}^{\infty} = 2.083 \cdot 10^{-3}\, S_{\text{out}} V_{\text{d.f.}} \gamma_{\text{c}} (x_{\text{f}} - x_{\infty})$, where $S_{\text{out}}$ – cross-section area of the working outside of timbering; $\gamma_{\text{c}}$ – coal density; $x_{\text{f}}$, $x_{\infty}$ – gas content of the face and residual gas content at atmospheric pressure.

Methane emission from loose coal in case of a production working is defined by the following relation:

$$I_{\text{lc}}^{\text{p.f.}} = 0.304 \gamma_{\text{c}} m_{\text{cs}} b_{\text{c}} v_{\text{cl}} (x_{\text{f}} - x_{\infty}) \times$$
$$\times \left\{ \exp\left[ -9.87 \frac{D}{R^2} \left( t_{\text{wc}} - \frac{l_{\text{lw}}}{v_{\text{dr}} + v_{\text{cl}}} \right) \right] - \exp\left( -9.87 \frac{D}{R^2} t_{\text{wc}} \right) \right\}, \quad (5)$$

where $b_{\text{c}}$, $v_{\text{cl}}$ and $v_{\text{dr}}$ – width of cut, conveying speed of the cutter-loader and drag conveyor respectively; $D$ and $R$ – coefficient of methane diffusion in loose coal and an average radius of a loose coal piece; $t_{\text{wc}}$ – duration of a winning cycle; $l_{\text{lw}}$ – longwall length.

According to formula (5), methane emission from loose coal in case of a production face depends on operating conditions of a cutter-loader and a drag conveyor.

When estimating methane emissions into the production face from underworked surrounding rocks, it is rational to take into account gas exchange of the rock blocks with transport fractures:

$$I_R = \frac{2 I_r(t) p_{\text{a}} \mu l}{L_l l_f \sqrt{\alpha k_b k_c} (p_0^2 - p_1^2)}, \quad (6)$$

where $I_r(t) = (0.5 L_l l_{\text{lw}} \sqrt{\alpha k_b k_c} / p_{\text{a}} \mu l)(p_0^2 - p_1^2) \exp(-0.5\beta t) I_0(0.5\beta t)$; $\beta = \chi \eta^{-1}$; $\eta = k_b^{-1} k_c l^2$; $I_R(\tau) = \exp(-\tau) I_0(\tau)$; $p_a$ and $\alpha$ – atmospheric pressure and geometry parameter of the porous-fractured environment of the mined-out space of the production face respectively; $\mu$ and $l$ – dynamic viscosity of the gas and average size of the rock block; $L_l$ – caving step of the main roof; $k_b$ and $k_c$ – gas permeability of the rock blocks and caving zone respectively; $p_1$ – pressure of the gas mixture in the mined-out space of production face on the floor level of the working seam.

Simulation experiments using relation (6) demonstrate that the greatest methane emissions occur sometime after the caving of the main roof. This fact is in good agreement with in-situ test results.

Non-dimensional value of methane emissions into the production face from overworked adjacent coal seam is calculated as follows: $J(\text{Fo}_f) = \text{Fo}_f^{-0.5} \exp(-\text{Fo}_f)$, where $\text{Fo}_f$ – Fourier filtration criterion. In order to forecast methane emissions into the production face from overworked adjacent coal seamthe following relation has been established:

$$I_{\text{o.r.}}(t) = 0.564 \frac{k_{\text{o.r.}} l_{\text{lw}} V_{\text{p.f.}} (p_0^2 - p_{\text{a}}^2)}{\mu p_0 H} \int_0^{\text{Fo}_f} \frac{\exp(-0.25/\tau)}{\sqrt{\tau}} \, d\tau, \quad (7)$$

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where $k_{o.r.}$ and $H$ – respectively gas permeability of the overworked rocks and thickness of the rocks in the floor of the working seam.

Calculations using formula (7) showed that methane emission in the production face from overworked adjacent coal seam are not so intensive as the ones from underworked adjacent seam.

**Mathematical models of gas dynamics in mining workings.** To ensure gas-dynamic safety of mining enterprises the issue of modeling air flow in mine workings is exceptionally relevant. Modeling of air dynamics is normally based on Reynolds set of equations which includes main conservation equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0; \tag{8}$$

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial x_j}\left(\rho u_j^* u_i^*\right) = -\frac{\partial p}{\partial x_i} + S_{ui} +$$

$$+ \frac{\partial}{\partial x_j}\left\{\mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu_{eff}\frac{\partial u_l}{\partial x_l}\delta_{ij} - \frac{2}{3}\rho\delta_{ij}\kappa\right\}; \tag{9}$$

$$\frac{\partial}{\partial t}\left(\rho H_1\right) - \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j H_1\right) = \frac{\partial}{\partial x_j}\left(\lambda\frac{\partial T}{\partial x_j} + \frac{\mu_t}{\mathrm{Pr_t}}\frac{\partial h}{\partial x_j}\right) + S_E +$$

$$+ \frac{\partial}{\partial x_j}\left\{u_i\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu_{eff}\frac{\partial u_l}{\partial x_l}\delta_{ij} - \frac{2}{3}\rho\delta_{ij}\kappa\right] + \mu\frac{\partial \kappa}{\partial x_j}\right\}, \tag{10}$$

equation of turbulence kinetic energy

$$\frac{\partial(\rho\kappa)}{\partial t} + \frac{\partial(\rho u_j \kappa)}{\partial x_j} = \frac{\partial}{\partial x_j}\left\{\left(\mu + \frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial \kappa}{\partial x_j}\right\} + S_\kappa +$$

$$+ \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} - \frac{2}{3}\left(\rho\kappa + \mu_t\frac{\partial u_l}{\partial x_l}\right)\frac{\partial u_k}{\partial x_k} - \rho\varepsilon, \tag{11}$$

equation of dissipation rate of turbulence kinetic energy

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left\{\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right\} + S_\varepsilon +$$

$$+ \frac{\varepsilon}{\kappa}\left\{c_{\varepsilon 1}\left[\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} - \frac{2}{3}\left(\rho\kappa + \mu_t\frac{\partial u_l}{\partial x_l}\right)\frac{\partial u_k}{\partial x_k}\right] - \rho c_{\varepsilon 2}\varepsilon\right\}, \tag{12}$$

where $\rho$ and $u_j$ – air density and components of the average air velocity ($j$ = 1, 2, 3) respectively; $u_i^*$, $S$ and $p$ – pulsating velocities ($i$ = 1, 2, 3), entropy and static air pressure respectively; $\mu_{eff}$, $\mu$ and $\mu_t$ – effective, dynamic and turbulent air viscosity respectively; $\delta_{ij}$ and $\kappa$ – Kronecker delta and turbulence kinetic energy; $H$ and $h$ – total and static enthalpy respectively.

Numerical solutions of Reynolds equations were found using finite element method. Calculation results for air velocity profile in the development face in case of a blowing air supply through central ventilation ducting are in good agreement with public data of laboratory and in-situ tests (Fig.2).

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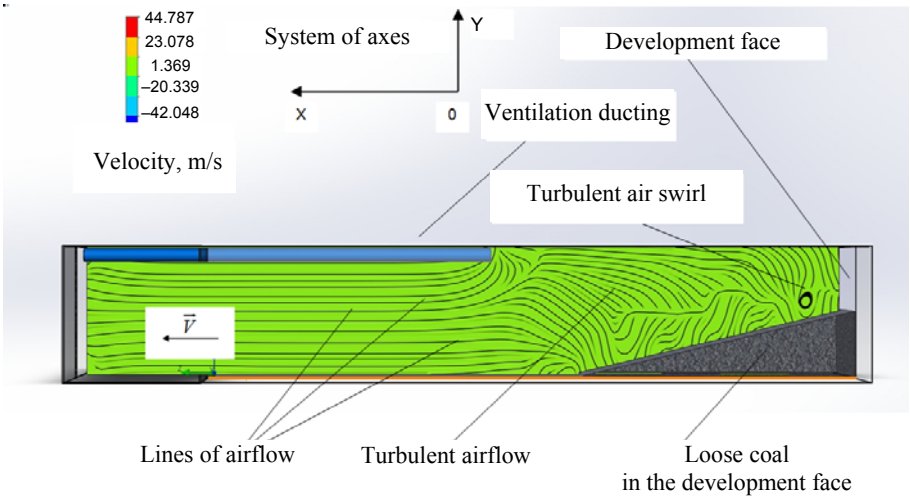



Fig.2. Structure of the turbulent stream in the face area of the development working

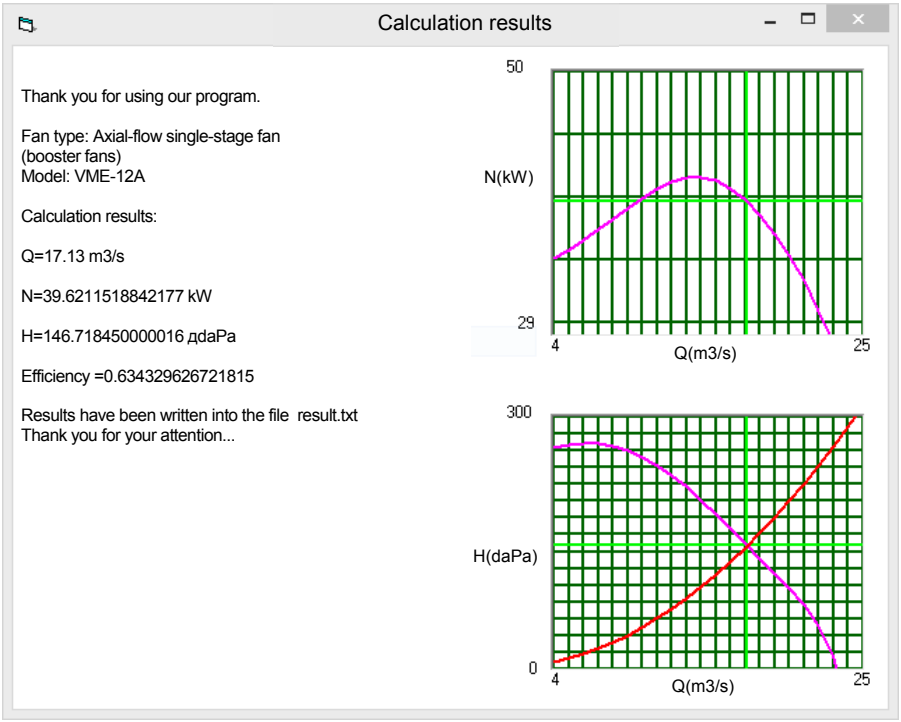



Fig.3. Program form for modeling fan operating conditions

Naturally, the next step is engineering analysis of modeling results and development of technical means to implement selected ventilation schemes.

Justification of ventilation modes, their mathematical modeling to solve practical ventilation issues using commercial mine fans is also one of the most important problems. It is reviewed through the example of operating conditions of booster fans [1].

**Mathematical models of air exchange for production and development areas.** The foundation of mathematical modeling for these processes is exact approximation of fan performance characteristics. It is a proven fact that approximation can be effectively carried out using software tools AutoCAD and Eureqa Pro. Exact approximations have been obtained for practically every booster fan produced in Russia. High accuracy of approximation allows to develop a computer program to model fan operating conditions at every stage of development working life cycle.

The program allows to define fan operating conditions for a specific network. Changing input data, simulation experiments can be carried out and fan operating conditions can be modeled for different ventilation networks. Suggested methodical approaches can also be used for main mine fans (Fig.3).

Forecasting gas situations in the production and development areas should be carried out using solutions to the equation of turbulent-convective gas diffusion in the airflow:

$$c(x,t)-c_H=\frac{DI_{\text{d.w.}}}{\Omega_{\text{d.w.}}}\left\{\left[1-\exp\left(-\frac{u_{\text{av}}}{L_{\text{d.w.}}}t\right)+0.5\exp\left(-\frac{u_{\text{av}}}{L_{\text{d.w.}}}t\right)\right]\int_0^t\exp\left(\frac{u_{\text{av}}}{L_{\text{d.w.}}}\tau\right)\times\right.$$

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$$\times\left[\exp\left(-K\sqrt{b}\right)\operatorname{erfc}\left(\frac{K}{2\sqrt{\tau}}-\sqrt{b\tau}\right)+\exp\left(K\sqrt{b}\right)\operatorname{erfc}\left(\frac{K}{2\sqrt{\tau}}+\sqrt{b\tau}\right)\right]d\tau\Bigg\}, \quad (13)$$

where $c$ – volume concentration of considered gas trace in the air of the working (for Kuznetsk basin methane or $CO_2$); $c_H$ – volume concentration of gas trace in the fresh stream; $D$ – average coefficient of turbulent diffusion of the gas trace in the air; $I_{\text{d.w.}}$, $\Omega_{\text{d.w.}}$ – absolute volume of gas and volume of the development working; $u_{\text{av}}$ – average air velocity in the development working; $L_{\text{d.w.}}$ – design length of the development working.

Result analysis for the simulation experiments using relation (13) demonstrate that, firstly, concentration patterns of gas traces in the air of production and development areas tend to a certain steady state, and secondly, dynamic calculation of air amount needed for ventilation of production and development areas should be carried out using solutions to the diffusion equation for steady-state condition. This finding allowed to develop methodic principles of dynamic calculation method for the assessment of air amount needed for ventilation of production and development areas in the mines with high methane- and $CO_2$-concentration.

Calculation of air amount needed for ventilation of production and development areas in case of extreme gas emissions in high $CO_2$-concentration mines is recommended to do as follows:

$$\frac{Q_{\text{f}}c_0+Ic_1}{Q_{\text{f}}+I+K_{\text{a}}S_{\text{d.w.}}L_{\text{d.w.}}}+\left(c_0-\frac{Q_{\text{f}}c_0+Ic_1}{Q_{\text{f}}+I+K_{\text{a}}S_{\text{d.w.}}L_{\text{d.w.}}}\right)\times$$

$$\times\exp\left[-\frac{(\beta+K_{\text{a}})S_{\text{d.w.}}}{Q_{\text{f}}}\int_0^{L_{\text{d.w.}}}\eta(x)dx\right]=\text{Maximum Allowance Concentration (MAC)}; \quad (14)$$

$$\frac{Q_{\text{o}}^{\text{e}}c_0+Ic_1}{Q_{\text{o}}^{\text{e}}+I+K_{\text{a}}S\left(l_{\text{air}}+l_{\text{p.w.}}\right)}+\left[c_0-\frac{Q_{\text{o}}^{\text{e}}c_0+Ic_1}{Q_{\text{o}}^{\text{e}}+I+K_{\text{a}}S\left(l_{\text{air}}+l_{\text{p.w.}}\right)}\right]\times$$

$$\times\exp\left[-\frac{(\beta+K_{\text{a}})S}{Q_{\text{o}}^{\text{e}}}\left(l_{\text{air}}+l_{\text{p.w.}}\right)\right]=\text{MAC}; \quad (15)$$

where $Q_{\text{f}}$, $I$ – air amount supplied to the face and «dead air» intake; $c_0$, $c_1$ – oxygen concentration in the atmosphere and «dead air» respectively; $S_{\text{d.w.}}$, $L_{\text{d.w.}}$ – cross-section area of the working and length of the development working; $\eta$, $K_{\text{a}}$ – coefficient of air supply and constant of air absorption by the outer surfaces of the coal seam; $\beta=\alpha+I/\Omega$; $Q_{\text{o}}^{\text{e}}$, $l_{\text{air}}$ – oxygen-based amount of air needed for ventilation of production working in case of extreme gas emissions and length of airway working respectively; $\alpha=Q/\Omega$.

Established relations allowed to develop a software complex for practical implementation of dynamic calculation method for air amount needed for ventilation of development and production workings in high $CO_2$-concentration mines in case of extreme gas emissions.

Similarly, methodic approaches have been developed to calculate air amount needed for ventilation of development workings in high methane concentration mines. The formula to estimate booster fan performance in the development working, taking into consideration convective transport of methane, is as follows:

$$Q_{\text{boost}}=I_{\text{d.w.}}\left[1-\exp\left(-\lambda_1\ln\lambda_2\right)\right]\times$$

$$\times\left\{\left(1+aL_{\text{d.w.}}\right)\left[\text{MAC}-c_{\text{f.a.}}\exp\left(-\lambda_1\ln\lambda_2\right)\right]-c_0\left[1-\exp\left(-\lambda_1\ln\lambda_2\right)\right]\right\}^{-1}, \quad (16)$$

where $c_0$, $c_{\text{f.a.}}$ – methane concentration in the fresh stream and in the face area respectively; $\lambda_1=\left(1+aL_{\text{d.w.}}\right)/L_{\text{d.w.}}$; $\lambda_2=\left(1-aL_{duct}\right)^{-1}$; $a$, $L_{\text{duct}}$ – loss coefficient and length of the ventilation ducting.

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Comparison of the results obtained using suggested method and current guidelines for designing coal mine ventilation systems [15] shows that consideration of diffusion gas transport allows to cut estimated air amount by 30-40 %. Consequently, dynamic method of vent calculation for productive and development areas using formulas (14)-(16), firstly, increases the validity of the air exchange model, and secondly, allows for a significant reduction of the ventilation costs.

Adjusted relations of loose coal degasification and gas-dynamic processes in the production areas allowed to develop a mathematical model for the performance optimization of mining equipment. Goal function characterizes energy consumption of the coal cutting process and permits to find an optimal match between coal cutting speed and cutter-loader feed taking into consideration limits on the cutting depth, factor of picks interference, installed engine capacity and gas factor. In-situ tests have been carried out using technical means to estimate initial rate of gas emission and natural gas content of the coal.

**Mathematical models of gas-dynamic consequences of underground coal mining.** Environmental model of geotechnological periods of underground coal mining demonstrates that gas-dynamic processes and related thermal processes must also be surveyed after mine abandonment (Fig.4), because rock dumps and mined-out spaces continue to have a negative impact on the atmosphere, water resources and soils.

To ensure environmental safety of underworked territories it is essential to clarify trends in gas exchange processes between mined-out spaces of high methane-concentration mines and the surface. Methane filtration from underworked areas to the surface happens due to excessive pressure of methane in the coal formation.

Methane emissions from underworked rock mass to the surface after coal mining completion:

$$I_{\Sigma}^{(\mathrm{m})}\left(\mathrm{Fo}_f\right)=\frac{0.282\langle k\rangle F_{\mathrm{s}}}{\mu p_{\mathrm{a}} H_0}\sqrt{\mathrm{Fo}_f}\left\{p_{\mathrm{a}}^2\left[1-\exp\left(-0.25\mathrm{Fo}_f\right)\right]+\right.$$
$$+2p_{\mathrm{a}}K_1\left[1+0.564\sqrt{\mathrm{Fo}_f}\exp\left(-0.25\mathrm{Fo}_f\right)-\mathrm{erf}\left(0.5\sqrt{\mathrm{Fo}_f}\right)\right]+$$
$$\left.+2.26K_{\mathrm{p}}^2 H_0\mathrm{Fo}_f^{-0,5}\left(1+0.25\mathrm{Fo}_f\right)\exp\left(-0.25\mathrm{Fo}_f\right)\right\}, \qquad (17)$$

where $\langle k\rangle$ – average gas permeability of the underworked rock mass; $F_{\mathrm{s}}$ – area of the underworked surface; $H_0$ – thickness of the zone of gas erosion; $\mathrm{Fo}_f$ – Fourier filtration criterion; $K_1$ – coefficient accounting for pressure increasing with depth.

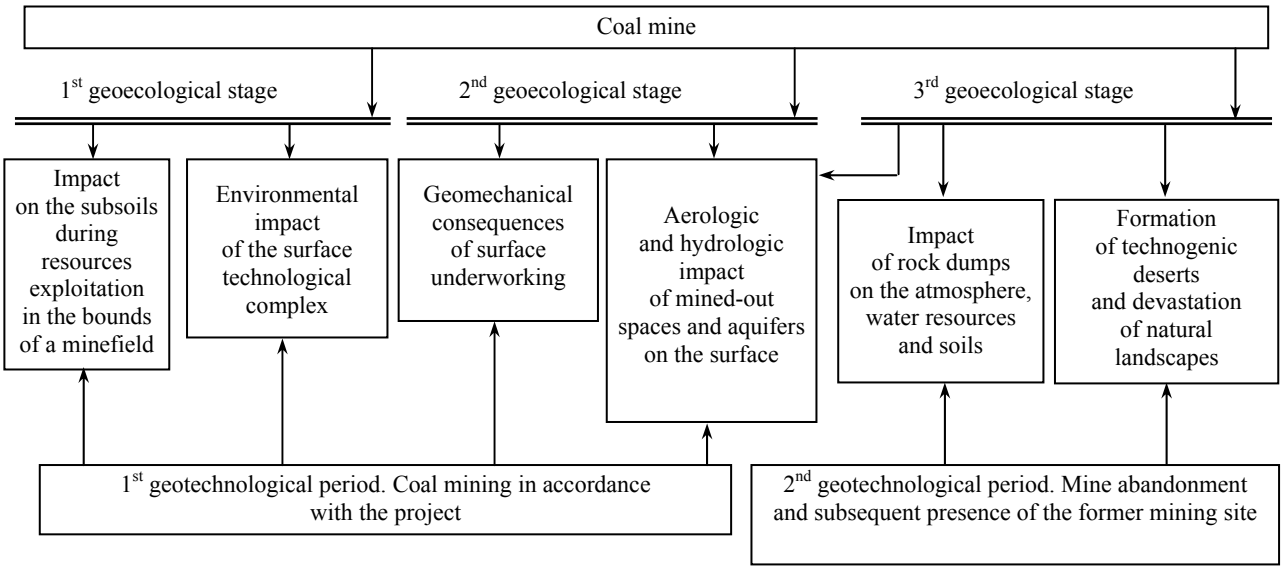



Fig.4. Environmental model of geotechnological periods of underground coal mining

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Expression (17) shows that methane emissions from underworked coal formation to the surface are essentially a function of Fourier filtration criterion. Results of simulation experiments give evidence that function (17) tends to an asymptotic value:

$$I_{\infty}^{(\mathrm{m})} = \frac{0.637\langle k\rangle F_{\mathrm{s}} K_{\mathrm{I}}^2}{\mu p_{\mathrm{a}}}. \tag{18}$$

According to formula (18), rate of methane emission from the underworked surface will be a constant for a significant period of time. «Dead air» filtration in underworked rock mass occurs at the drop of atmospheric pressure. Mathematical model of this process is presented below:

$$I_{\mathrm{sp}}^{\mathrm{f}} = \frac{2\langle k\rangle}{\mu_{\mathrm{d.a.}} H}\left(p_{\mathrm{d.a.}}^{(\mathrm{n})} + \alpha_P t\right), \tag{19}$$

where $\mu_{\mathrm{d.a.}}$ – dynamic viscosity of «dead air»; $p_{\mathrm{d.a.}}^{(\mathrm{n})}$ – stable-state pressure in the mined-out space; $\alpha_P$, $H$ – rate of atmospheric pressure decrease and thickness of underworked rock mass.

Noticeably, structure of the formula (19) and results of the modeling experiment are in good accordance with the quality estimations of gas emission from mined-out spaces. It has been proved experimentally that the rate of gas emissions caused by a decrease in atmospheric pressure is proportional to the rate of pressure decrease.

An important effect of gas-dynamic processes on the mine surface is reflected in thermal processes of spontaneous coal heating. Results of mathematical modeling of oxygen diffusion in the coal accumulation permit to justify the following relation of coal heating on the surface of a rock damp:

$$\frac{T(x,t)-T_0}{T_{\mathrm{c}}-T_0} = \operatorname{erfc}\frac{x}{2\sqrt{at}} - \frac{w_0}{\lambda k_*^2 (T_{\mathrm{c}}-T_0)}\left[\operatorname{erfc}\frac{x}{2\sqrt{at}} - \exp(-k_* x) - \frac{1}{2}\exp\left(k_*^2 at - k_* x\right)\times\right.$$
$$\left.\times \operatorname{erfc}\left(k\sqrt{at} - \frac{x}{2\sqrt{at}}\right) + \frac{1}{2}\exp\left(k^2 at + kx\right)\operatorname{erfc}\left(k\sqrt{at} + \frac{x}{2\sqrt{at}}\right)\right], \tag{20}$$

where $T(x,t)$, $T_0$ and $T_{\mathrm{c}}$ – temperature profile in the coal accumulation, initial temperature and surface temperature respectively; $a$, $\lambda$ – temperature and thermal conductivity of coal accumulation; $w_0$, $k_*$ – energy output of the heating source and space relaxation coefficient for oxygen concentration.

Modeling results for experiments using expression (20) show that temperature profile of the coal accumulation has a peak corresponding to the highest coal temperature in a given moment. This point moves further into the accumulation and highest temperature of coal increases. Thus, simulation experiments in the course of environment surveying can help forecasting thermophysical processes in rock dumps by a factor of endogenous fires.

This being said, it is geotechnological approaches to solving environmental issues of mining regions that turn out to be most effective. E.g., new technologies developed in Tula State University provide effective schemes of underground coal gasification (UCG) that are very promising for Moscow basin. Power gas from UCG is used by local power stations that supply energy to companies that develop technogenic deposits. These geotechnologies will permit complex development of remaining resources and technogenic deposits.

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