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DEVELOPMENT OF ENERGY-SAVING TECHNOLOGIES PROVIDING COMFORTABLE MICROCLIMATE CONDITIONS FOR MINING

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The paper contains analysis of natural and technogenic factors influencing properties of mine atmosphere, defining level of mining safety and probability of emergencies. Main trends in development of energy-saving technologies providing comfortable microclimate conditions are highlighted. A complex of methods and mathematical models has been developed to carry out aerologic and thermophysical calculations. Main ways of improvement for existing calculation methods of stationary and non-stationary air distribution have been defined: use of ejection draught sources to organize recirculation ventilation; accounting of depression losses at working intersections; inertance impact of air streams and mined-out spaces for modeling transitory emergency scenarios. Based on the calculation algorithm of airflow rate distribution in the mine network, processing method has been developed for the results of air-depressive surveys under conditions of data shortage. Processes of dust transfer have been modeled in view of its coagulation and settlement, as well as interaction with water drops in case of wet dust prevention. A method to calculate intensity of water evaporation and condensation has been suggested, which allows to forecast time, duration and quantity of precipitation and its migration inside the mine during winter season. Solving the problem of heat exchange between mine airflow and timbering of the ventilation shaft in a conjugation formulation permits to estimate depression value of natural draught and conditions of convective balance between air streams. Normalization of microclimatic parameters for mine atmosphere is forecasted for the use of heat-exchange units either heating or cooling and dehumidifying ventilation air. Algorithms are presented that permit to minimize ventilation energy demands at the stages of mine design and exploitation.

***Key words*:** energy-saving technologies, air distribution, heat and mass transfer, mine microclimate, ventilation management

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Introduction. State of mine atmosphere is defined by five main air parameters – airflow, temperature, humidity, gas and dust content. These parameters depend on numerous factors, have different values at different points of the ventilation system and change over time. Each of the abovementioned air characteristics defines comfortable conditions of mining and has threshold criteria, failure to fulfill which leads to accidents threatening safety of humans and soundness of equipment.

Modern mines represent complicated dynamic systems, subject to natural changes like temperature and humidity shifts, as well as technogenic ones. Artificial changes occur due to human activity: developing new planes, adding new production areas and mine workings, vent connections, stoppings, draught sources etc. All this has a huge impact on air movement, purity and thermodynamic characteristics in specific workings and in the mine as a whole, and all the changes should be predictable in order to prevent emergency situations. Certainly, all mentioned characteristics depend not only on air processes, but also on heat and mass transfer in the rock formation and mining equipment that are in contact with the air flow. Air is set in motion by various fan types, exchanges heat with the rocks – this interaction also leads to changes in humidity (evaporation-condensation) and gas content (gas emission and sorption) – gets heated by calorifers or cooled by refrigerators, gets saturated with dust and contaminants in the working areas from mining equipment. Hence, the system «mine airflow – rock formation – mining equipment» is interconnected and it is impossible to separate a subsystem related solely to the mine airflow. Modeling of this system requires a wide range of physical and mathematical models integrated in one software environment to obtain a complete and exact picture of the process in question.

Energy-saving technologies providing comfortable microclimate conditions for mining are being researched at the department of aerology and thermophysics of the Mining Institute, Ural bunch of the Russian Academy of Sciences, basing on modeling mining aerologic processes in four main fields: 1) improvement of calculation methods for stationary air distribution and air-dynamic char-

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acteristics of ventilation systems of mining enterprises; 2) modeling heat and mass exchange processes in the air and rock formations; 3) development of modeling methods for high-speed emergency processes; 4) development of energy-saving approaches to ventilation management. There is a trend to integrate all these fields in order to review ventilation as a single aero-thermo-gasdynamic process. Due to rapid development of computer science in the latest decade, a significant progress has been made in complex multiple-factor modeling of underground aerologic processes, especially in application of numerical methods and practical use of the results in providing safe conditions of mining. The first field of modeling, related to solving network problem of air distribution, is the basic one, because in the longer run models of the second (heat and mass transfer) and fourth fields (ventilation management) require network adaptation, and the third field is a modification of the first one in the view of air streams inertance and compressibility of the air in mined-out spaces. Currently, proportionate to growing capacity of computers, more reliable and rapidly converging numerical methods of solving sets of network equations are gaining ground, as they possess guaranteed rapid convergence but require significant amount of RAM [5].

If the rate of investigated aerologic process is not high, the modeling is done using quasi-stationary approximation. The process is expressed as a sequence of stationary states repeatedly calculated at every time step with updatable processing data. Most models of standard mine ventilation are used for practical calculations in this approximation. The main factor, defining dynamics of heat depression in the mine, is heat exchange of the rock mass with the air flowing through mine workings. As the intensity of heat exchange depends on how rapidly and deeply temperature fluctuations penetrate the rock, the calculation problem of heat exchange in the rock is closely related to modeling of aerologic processes.

Methods and models. Taking into account all factors, significant for the modeling process, the structure of developed and improved mathematical models and calculation methods for mining aerologic processes can be presented as follows:

1. Development of methods to forecast air stream movements along mine workings follows the path of accounting for the greatest possible scope of natural and technogenic factors, defining the dynamics of air distribution in the mine network.

• Modeling the operation of ejection installations to organize recirculation ventilation permits to make significant improvements in the ventilation of working zones with minimal energy requirements [2, 4, 14].

Fig.1 and 2 demonstrate several variations of ejector capacity calculation Q_2 in the working with a cross-section area of 8 m^2 using fan VM-12A without contraction as a function of cross section area of the mixing chamber S for different resistance values R_{34} (in kμ) – total resistance of parallel sections, – working section 4 and losses 3. R_1, resistance of the grid before vent connection containing an ejector, is considered equal to 0.01 kμ, main fan depression – 500 mmHg. The calculations are carried out using the ejection model based on the principle of momentum conservation, adjusted to momentum losses due to compression – expansion of the airflow in the mixing chamber [4]. Analysis of results (Fig.2) shows that for the scheme in question (Fig.1) the ejector installation based on VM-12A fan will be more productive than the same fan located in the vent connection provided that the resistance of ventilation sections $R_{34} < 0.0001$ kμ, i.e if $R_1/R_{34} > 100$. Otherwise the use of the ejector has no positive effect.

• Depression losses at the conjunctures are high for places where the shaft meets the production zone and air heating duct, as well as any conjunctures of large workings.

Results of numerical tests show that growth in size and complexity of ventilation systems leads to increasing impact of conjunction resistance on air distribution. The contribution of conjunction resistance into airstreams distribution also rises with increasing cross-section area of the workings S_i. This is explained by the fact that linear resistances of the workings are inversely proportionate to $S_i^{2.5}$ [15], whereas for the resistance $R_i \sim 1/ S_i^2$. With S_i increasing, linear resistances decrease, and the contribution of conjuncture resistance share grows.

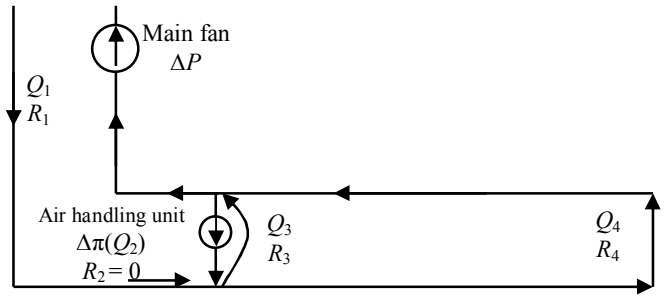


Fig.1. Mine ventilation scheme with an additional fan

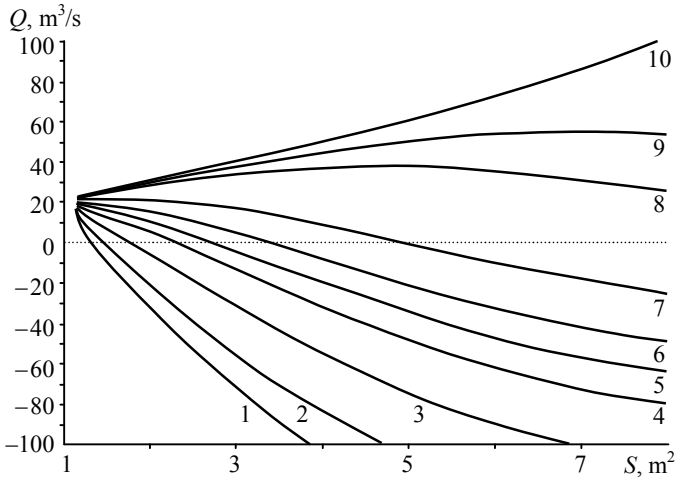


Fig.2. Ejector capacity as a function of cross-section area of the mixing chamber for different values of total aerodynamic resistance R_{34}

1 – R_{34} = 0,01 кμ; 2 – 0,005; 3 – 0,002; 4 – 0,001; 5 – 0,0007; 6 – 0,0005; 7 – 0,0003; 8 – 0,0001; 9 – 0,00004; 10 – 0,00001

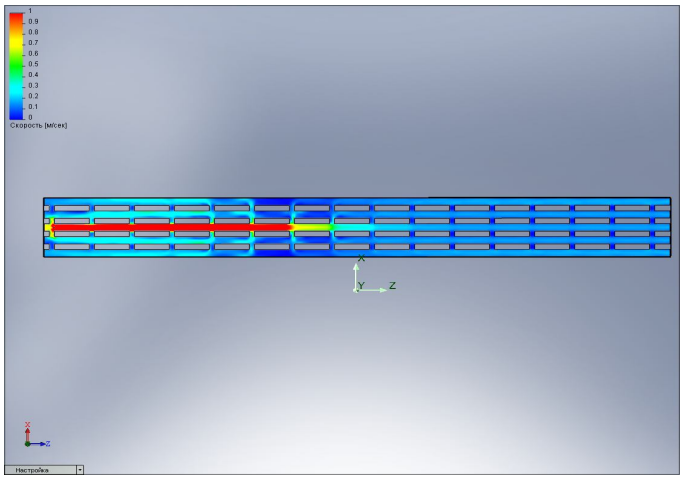


Fig.3. Air velocity in the group of five parallel open workings, diameter 10 m, distance between vent connections 50 m, ventilation equipment – ejector fan VME-12A

Analytical relations obtained for the calculation of local aerodynamic resistances [11] permit to carry out analytical modeling of air distribution for such mine sections, where standard calculation methods are useless (Fig.3).

• Inertance of air streams shows in modeling of emergency situations like mine fires, shutoff and reversing of the main fan [7, 17].

A distinctive feature of emergency situations is their unsteadiness, when in seconds air velocity significantly changes in value and, possibly, in direction. Normally such unsteady processes are transitory, because in a short period of time one stationary (or quasi-stationary) ventilation mode changes the other. As in the process of such transition large air masses gain or lose momentum, neglecting the inertance of these masses produces the bigger error the quicker the transition occurs (Fig.4).

• Impact of the mined-out spaces on transition processes of non-stationary air distribution after shutoff or reversing of the main fan can be modeled only by solving the general equation set, whereas specialized calculation methods for network equations turn out to be inadequate to describe the movement of compressible media [10].

Presence of large mined-out spaces has no effect on stationary ventilation modes. However, during transitory ventilation processes caused by rapid changes in depression of draught sources (shutoff or reversing) the impact of mined-out spaces can be quite large. Millions of cubic meters of air underground turn into a pressure accumulator of a kind, which keeps its constant value by way of air compression – expansion several minutes after the fan is shut off or reversed. The air itself moves like compressible media and it can enter or exit the mine through any shaft, formally breaking the first law of networks, used in modeling air distribution under the condition of uncompressible air.

Considering the balance of air consumption Q in the junctions non-zero allows to model the impact of mined-out spaces on the dynamics of airflow in transitory modes of ventilation:

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$$\sum_j Q_j^{(k)} = -\frac{\Delta P^{(k)}}{2P_{\text{atm}}\Delta t}\sum_j L_j^{(k)} S_j^{(k)} \quad ,$$

where summation is carried out over j^{th} workings, incident with k^{th} junction; L and S – their lengths and cross-section areas, m and m^2; ΔP – change of air pressure in the junction in time period Δt (s); P_{atm} – atmospheric pressure, Pa.

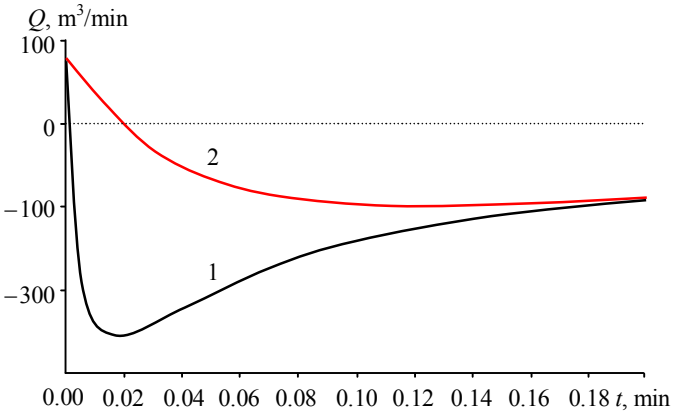


Fig.4. Calculated changes in air amount in a slope working during fire accident (100 MW for 10 m)
1 – inertance not considered; 2 – inertance considered

• Method of calculating aerodynamic resistances of mine workings using results of air-depressive surveys is based on the calculation algorithm of airflow rate distribution under conditions of data shortage [1, 12].

The number of gauges and their location should be chosen using the principle of providing air distribution forecasts with a minimal number of devices. It permits to define airflow rate in a functional and reliable way, at the same time reducing capital and operational costs of the system design and exploitation (Fig.5).

2. In most cases, the most feasible description of contaminants transfer is based on the model of ideal displacement, when particles of gas or smoke are passively displaced by the airflow with a possibility of sorption by the rock mass surface. Dust distribution is modeled taking into account its coagulation and precipitation, as well as interaction with water drops in case of wet dust prevention [13].

In order to calculate concentration of dust in the air, flowing through the mine working under the influence of aforementioned factors, an analytical expressions to assess the effectiveness of dust prevention system has been obtained:

$$C = C_0 \exp\left\{-\left[\frac{4.88}{Pe}\sqrt{203.77+\left(\frac{a\text{Pe}}{V}\right)^2\left(\frac{7Ah}{a}\right)^{4/7}}-\frac{66.77}{\text{Pe}}\right]\frac{X}{h}\right\},$$

where $a \equiv \frac{2}{9}\frac{g(\rho-\rho_a)}{\rho_a \nu_m}$ – Stokes number, 1/(m·s); $A \equiv \frac{D\mu r_o^3}{\rho_a RT}\Delta P$, m^5/s; $\text{Pe} \equiv \frac{Vh}{D_m}$ – turbulent Peclet number; V – air velocity, m/s; h – working height, m; D –molecular diffusion coefficient of water vapors to the particle, m^2/s; μ – molar mass of water vapors, kg/mol; R – universal gas constant; T – absolute air temperature, K; ρ – dust matter density, kg/m^3; ρ_a – air density, kg/m^3; r_o – initail size of dust particles, m; ΔP – initial drop in water vapor elasticity over the particle, Pa; ν_m and D_m – coefficients of turbulent viscosity and diffusion, m^2/s.

3. Transfer of water, unlike gas and dust, is closely linked to air temperature changing while it is moving. Basing on the initial estimates of temperature fluctuations intensities of water evaporation and condensation are calculated, which allows to predict time, duration and quantity of precipitation and its migration inside the workings in winter season [6].

In the majority of mines air, while it is flowing through the working, receives water and by the time it reaches ventilation shaft its relative humidity is around 90-95 %. In the conditions of «Skalisty» mine, e.g., air has a temperature of 18 °C, humidity 90 %, and then rises to the height of more than 1 km. As a result of hydrostatic cooling of the air, starting from a certain point where humidity reaches 100%, intensive condensation starts followed by heat emission, which compensates for exhaustion air cooling. Fig.6 demonstrates results of modeling tests and measurement points of this thermodynamic effect, showing how unaccounted heat emissions lead up to

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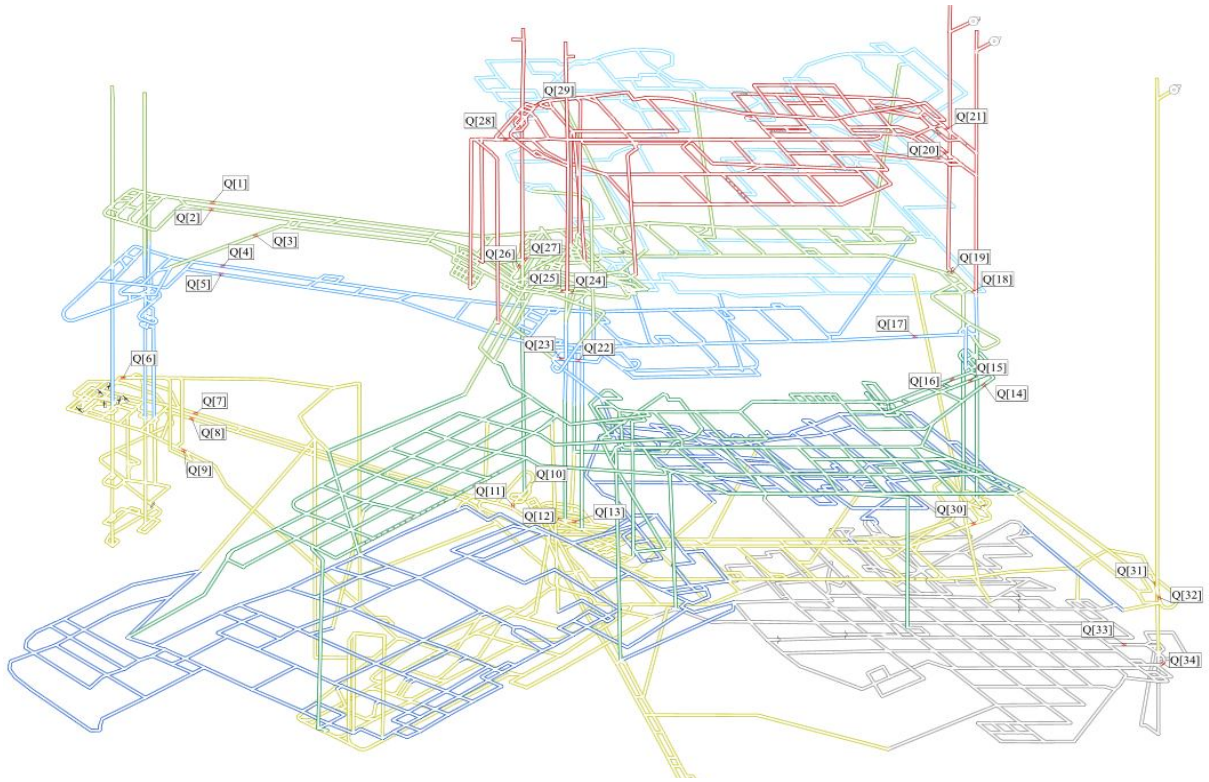


Fig.5. Locations of automated gauge stations in the ventilation system of «Taymyrsky» mine

an error of 4 °C downward. Such error can lead to significant mistakes in estimation of overall mine natural draught, which impacts the intensity of mine ventilation and through the air amounts in separate workings influences their thermodynamic processes.

Analysis of in-situ data and results of numerical modeling of water-exchange processes in potassium mines indicates that winter migration of condensed brines depthward is inevitable, occurs in the range of 3 km from ventilation shaft and leads to transfer of approximately 1/10 share of summer precipitation. Thus the only way to prevent it is to dry the air during warm season using air handling systems, e.g. calorifers operating in cooling mode. Estimations show that during summer season the use of calorifer can remove up to 6000 t of water from the air, which significantly reduces amounts and zone of its precipitation, as well as its subsequent migration into the depth of the mine.

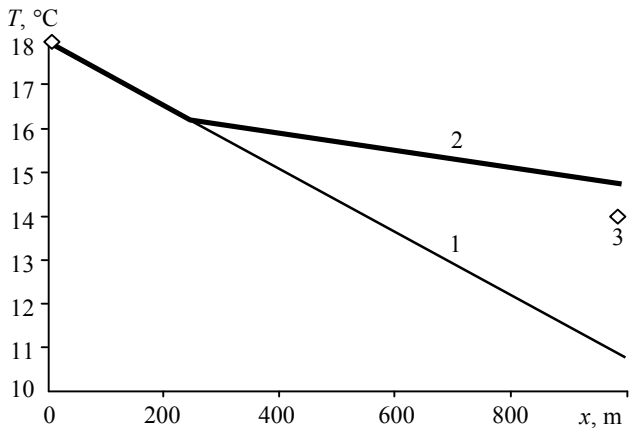


Fig.6. Calculation results for air temperature in the ventilation shaft not considering (1) and considering (2) heat emission caused by water condensation; 3 – results of experimental tests

4. Crude estimations of the heat transfer can be carried out using the model of ideal displacement with a set rate of heat exchange with the rock mass or in a conjunction formulation. Specific effects of shaft temperature conditions have to be taken into consideration – geothermal increase of rock temperatures with depth, air heating due to its hydrostatic compression.

• Heat exchange rate is not a set or constant value. It is calculated either using analytical expressions of various complexity levels, or an exact solution to the heat exchange problem in a conjunction formulation [7].

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Processes of heat exchange between ventilation air and rock mass have a significant influence on microclimate of the mine. Due to heat exchange, perceptible (several degrees) seasonal and daily heat variations of the ventilation air only occur in the range of 1-2 km from conjunction areas between the ventilation shaft and the intake horizon. Further from the shaft the air receives temperature of the rock mass, which results in constant climatic parameters that stay the same all year long. The most intensive heat exchange between the air and the rock mass occurs in ventilation shafts (Fig.7).

• Complex dynamics of thermal depressions is described by a model of airstream stratification in the mine workings, using which allows to obtain analytically a realistic picture of air movement in the zone of mine fires, as well as in ventilation shafts after main fan shutoff [9, 18].

In case of fire, one of possible measures to suppress it and to prevent the distribution of combustion products in the mine workings is main fan shutoff, after which the only source of air coming into the mine will be natural draught. Despite the fact that the impact of natural draught on the airflow is well understood, this ventilation issue has not been researched for mines with a one-level shaft. However, experimental and modeling test show that under certain conditions after the fan shutoff mine ventilation continues at the rate of 1/10 to initial air supply. At the same time the airflow in the shafts is ambiguous and hard to predict (Fig.8).

• To normalize microclimate parameters of the mine atmosphere, heat exchange installations can be used that work either in heating or cooling mode and dehumidify ventilation air [3].

In the course of mathematical modeling of heat and water exchange, analytical expressions have been obtained that permit to calculate distribution of air and heat conductor temperatures across the length of heat-exchange tubes, as well as surface locations of water condensation when

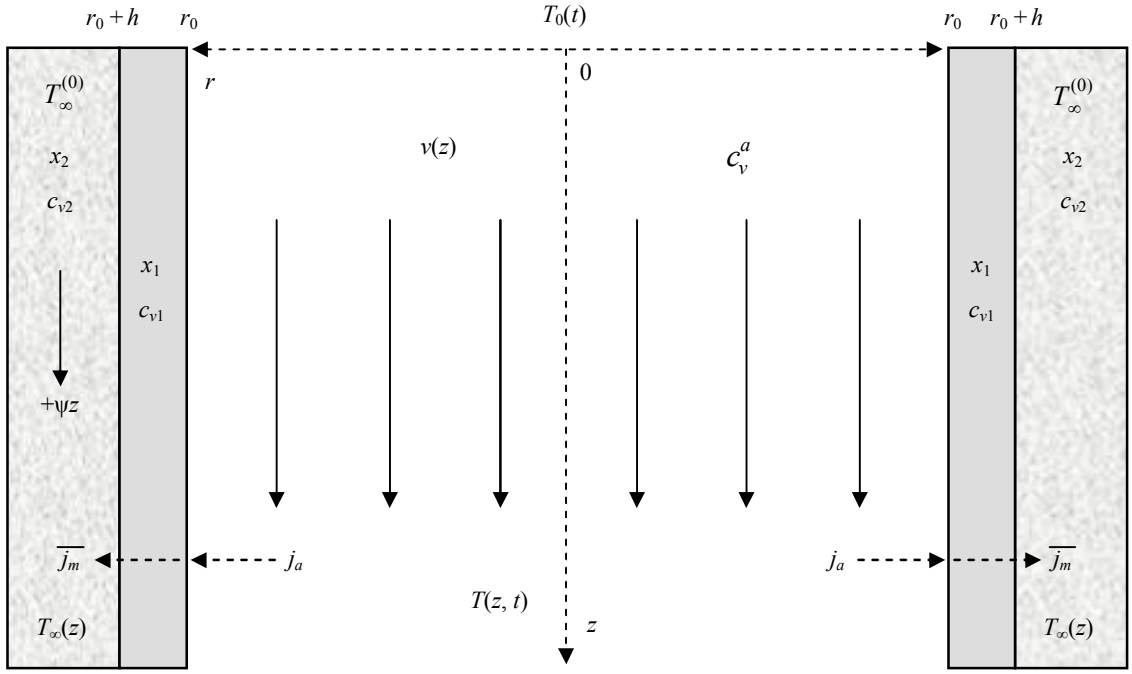


Fig.7. Two-layer problem of heat exchange between mine air and ventilation shaft timbering

r and z – radial and vertical coordinates, m; t – time, s; c_v^a, c_{v1} and c_{v2} – volume thermal capacity of air, first (iron) and second (concrete and rock mass) layers, J/m^2/s; x_1 and x_2 – temperature conductivity of the first (iron) and second (concrete and rock mass) layers, m^2/s; r_o – shaft radius, m; h – thickness of the first layer, m; $v(z)$ – air velocity, m/s; $T_\infty^{(0)}$ – average annual air temperature, °C; $T_\infty(z) = T_\infty^{(0)} + \psi z$ – temperature of «intact rock mass», °C; $1/\psi$ – value of geothermal step, м; $T_0(t)$ – outer air temperature, °C; $T(t, z)$ – current air temperature at the depth z, °C; j_a and j_m – density of heat current: in the air – towards the boundary, in the rock mass – from the boundary, J/(s·m^2)

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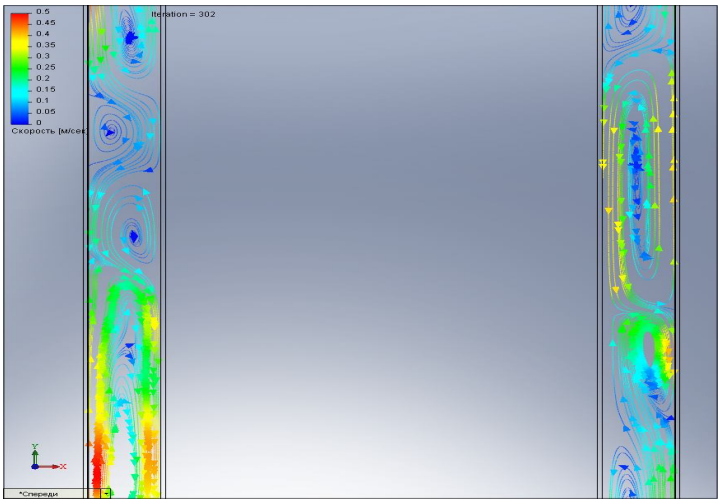


Fig.8. Convective flow of air streams in the shafts after draught source shutoff

the air cools down (Fig.9). Obtained formulas allow to estimate not only local characteristics – predictable locations of water freezing in case of air heating and water condensation in case of air cooling – but also integral characteristics: average output air temperature and heat capacity of the installation. Based on the following analysis of their dependence from location and connection of heat-exchange modules, as well as directions and locations of water feed, conclusions are drawn regarding the optimal configuration of the system.

5. Development of energy-saving ventilation technologies is driven by the need to provide every mining area with the necessary amount of fresh air spending minimal amounts of energy.

For this reason an algorithm of optimal regulation of air distribution has been developed using negative regulation with minimal load on the main fan [8].

The algorithm has been computationally implemented basing on mesh current method and permits to find optimal solutions in automatic mode given set parameters of the ventilation network; the algorithm can be used to design ventilation systems (Fig.10).

In case there is not enough data on the parameters of the network, information is read from the gauges, but the algorithms works very slowly due to large amount of operations [16]. In such case, real-time ventilation management happens on the basis of a simplified algorithm, which can be edited in difficult situation when such need arises.

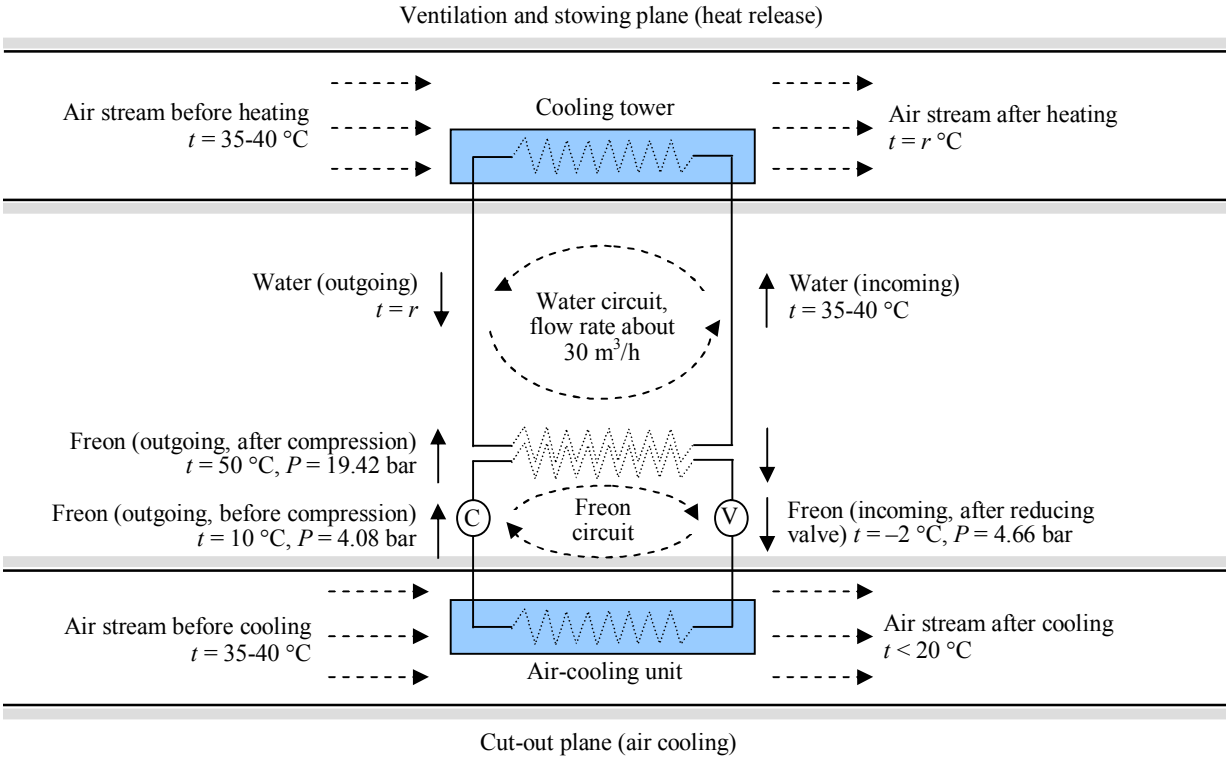


Fig.9. Scheme of mine air cooling system

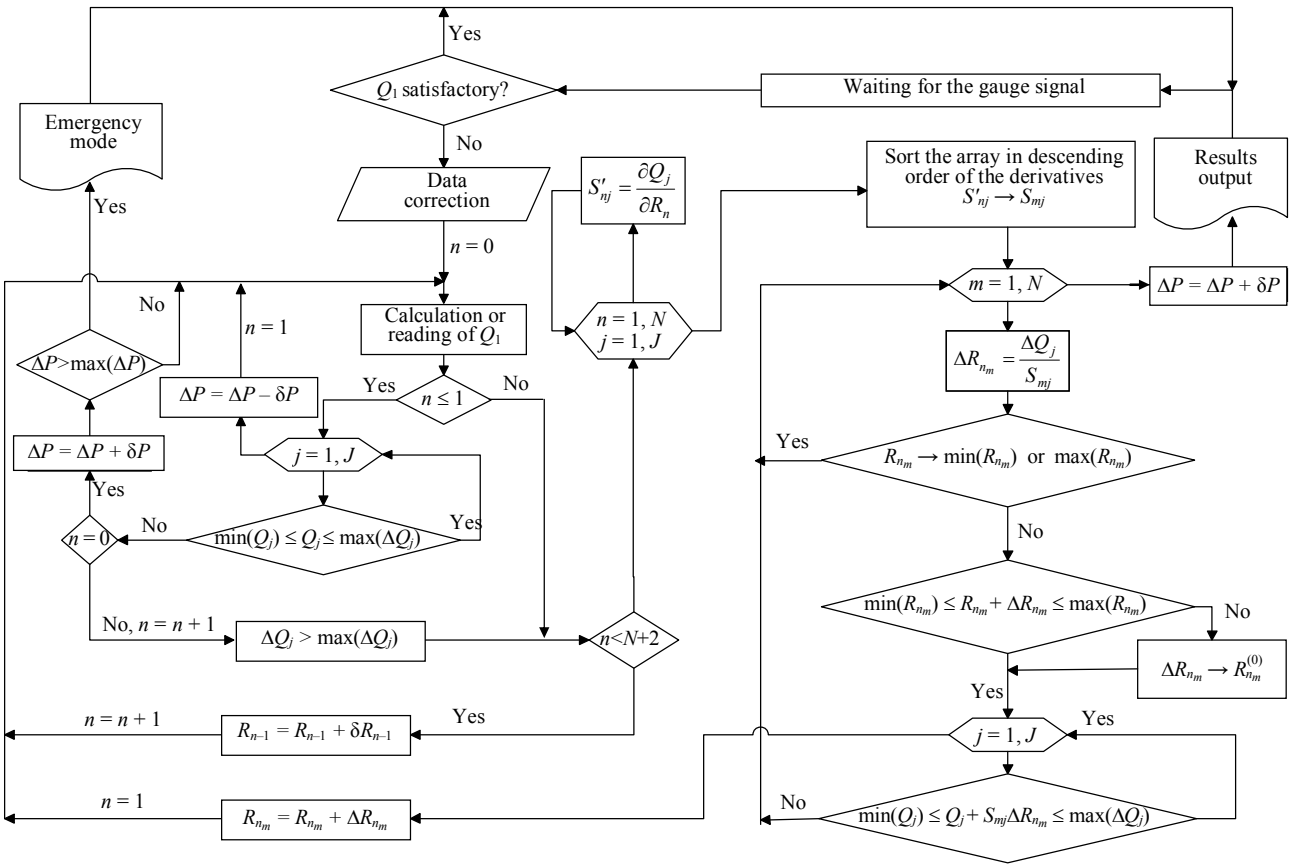


Fig.10. Control-flow chart of ventilation optimization using the system of negative regulation with minimal load on the main fan

Selection of optimal parameters for the main fan is done through regulation of impeller's rotation rate n_j, for ventilation constructions - through regulation of cross-section area of airpassages S_k;

$$\begin{cases} \Delta n_j = A\left(\dfrac{\sum\limits_{j=1}^{N_{\text{MF}}} n_j^2}{N_{\text{MF}} n_j^2} I_{ij(def)} \max \Delta Q_i^+ - \dfrac{N_{\text{MF}} n_j^2}{\sum\limits_{j=1}^{N_{\text{MF}}} n_j^2} I_{ij(res)} \min \Delta Q_i^-\right) - C \min \Delta S_i; \\ \Delta S_k = B\left(\dfrac{\sum\limits_{k=1}^{N_{MNR}} R_k Q_k^2}{N_{\text{MNR}} R_k Q_k^2} I_{ik(def)} \max \Delta Q_i^+ - \dfrac{N_{\text{MNR}} R_k Q_k^2}{\sum\limits_{k=1}^{N_{MNR}} R_k Q_k^2} I_{ik(res)} \min \Delta Q_i^-\right), \end{cases}$$

where A, B, C – empirical regulation parameters; n_j – impeller's rotation rate for j^{th} main fan; R_k – aerodynamic resistance of k^{th} measure of negative regulation; Q_k – rate of airflow passing through k^{th} ventilation construction; $N_{\text{MF (MNR)}}$ – number of main fans (measures of negative regulation); $I_{ij(ik)}$ – influence matrix, characterizing the influence of j^{th} fan (k^{th} ventilation construction) capacity on the airflow rate in each i^{th} working; ΔQ_i – error of resources management (deviation of the actual amount from the required one).

Conclusion. Research of the authors did not amount to the fields mentioned in the paper, corresponding to specialization profile of the Department of Aerology and Thermophysics of the Mining Institute. In the last few years active development has been seen in research areas of allied sciences not directly relevant to mining aerology. Among these are modeling of ore streams to opti-

mize conveyor transportation and investigation of ice wall properties used in shaft mining. Above-mentioned models of aerologic processes are being improved and computationally implemented in the analytical complex «AeroNet», aimed at practical application in the field of development and implementation of energy-saving technologies to provide comfort microclimate conditions at mining enterprises.

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