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STUDY OF AERO- AND THERMODYNAMIC PROCESSES OCCURRING ON THE FIRST STAGE OF THE CROSS-VENTILATION CREATION IN MINE

L.Iu. Levin, M.A. Semin, Iu.A. Kliukin, E.V. Nakariakov

Mining Institute of the Ural Branch of the Russian Academy of Sciences (78a Sibirskaia str., Perm, 614007, Russian Federation)

ИССЛЕДОВАНИЕ АЭРО- И ТЕРМОДИНАМИЧЕСКИХ ПРОЦЕССОВ, ПРОТЕКАЮЩИХ НА НАЧАЛЬНОМ ЭТАПЕ ОРГАНИЗАЦИИ СКВОЗНОГО ПРОВЕТРИВАНИЯ РУДНИКА

Л.Ю. Левин, М.А. Семин, Ю.А. Клюкин, Е.В. Накаряков

Горный институт Уральского отделения Российской академии наук (614007, Россия, г. Пермь, ул. Сибирская, 78а)

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mine construction, cross slit between shafts, mine ventilation, Kirchhoff`s laws, tunneling fan, natural draft, mathematical model, transient processes, air inertia, air distribution stability, convective separation, numerical simulation, ideal displacement model, diffusion, turbulence model.

This article presents the study of transient processes occurring in the mine ventilation network of Usolskii potash plant during pit bottom`s construction after completion of sinking cross slit between shafts in the cold season. Parameters of aero- and thermodynamic processes that influence the organization of through stream in the construction of the mine with the central ventilation scheme are determined. Within the one-dimensional formulation based on Kirchhoff's laws a mathematical model of air flow based on time-varying effect of natural draft was constructed taking into account the inertia of the air. A comparison of data obtained in the one-dimensional formulation was conducted with the results of numerical modeling of three-dimensional air flow with different thermodynamic parameters in complex software ANSYS. The numerical calculation was made using the model of a perfect gas, k-ε-turbulence model with wall functions which had an additional term to account for the roughness of the walls. The comparative analysis showed solutions compliance in one-dimensional formulation and three-dimensional numerical simulation for an initial period of time and after the establishment of stationary air distribution. In the period of time characterized by the transition from the peak airflow to its steady-state value, there is a significant mismatch of studied variables over time. Predicting the time of transient processes in mine ventilation system after sinking cross slit between shafts should be implemented on the base of calculations carried out using methods of computational fluid and gas dynamics. Calculation of peak values and stationary parameters of aero- and thermodynamic processes for development of technical solutions for the organization of ventilation`s design schemes may be carried out in the framework of one-dimensional setting.

Ключевые слова:
строительство рудника, межстволовая сбойка, рудничная вентиляция, законы Кирхгофа, проходческий вентилятор, естественная тяга, математическая модель, переходные процессы, инерционность воздуха, устойчивость воздухораспределения, конвективное расслоение, численное моделирование, модель идеального вытеснения, диффузия, модель турбулентности.

Представлено исследование переходных процессов, возникающих в вентиляционной сети рудника Усольского калийного комбината, на этапе строительства околоствольного двора после завершения проходки межстволовой сбойки в холодный период года. Определены параметры аэро- и термодинамических процессов, оказывающих влияние на организацию сквозной струи при строительстве рудника с центральной схемой проветривания. В рамках одномерной постановки на базе законов Кирхгофа построена математическая модель течения воздуха с учетом переменного во времени влияния естественной тяги, в которой учтена инерционность воздуха. Проведено сопоставление данных, полученных в одномерной постановке, с результатами численного трехмерного моделирования течения воздуха с различными термодинамическими параметрами в программном комплексе ANSYS. Численный расчет произведен в рамках модели совершенного газа, *k*-ε-модели турбулентности с пристеночными функциями, имеющими дополнительное слагаемое для учета шероховатости стенок. В результате сравнительного анализа выявлено соответствие решения задачи в одномерной постановке и трехмерного численного моделирования для начального промежутка времени и после установления стационарного воздухораспределения. Во временном промежутке, характеризующемся переходом от пиковых расходов воздуха к их стационарным значениям, наблюдается существенное рассогласование исследуемых величин во времени. Прогнозирование времени протекания переходных процессов в вентиляционной сети рудника после завершения проходки межстволовой сбойки необходимо осуществлять на основе расчетов, выполненных с использованием методов вычислительной динамики жидкости и газа. Расчет пиковых и стационарных значений параметров аэро- и термодинамических процессов для разработки технических решений по организации проектной схемы проветривания можно осуществлять в рамках одномерной постановки.

Lev Iu. Levin (Author ID in Scopus: 16407072500) – Doctor of Technical Sciences, Head of the Department of Aerology and Thermal Physics (tel.: +007 342 216 09 69, e-mail: aerolog_lev@mail.ru).
Mikhail A. Semin – Researcher, PhD of Technical Sciences (tel.: +007 342 216 54 92, e-mail: mishkasemin@gmail.com). The contact person for correspondence.
Iurii A. Klukin – Leading Design Engineer (tel.: +007 342 216 54 92, e-mail: aeroyuri@gmail.com).
Evgenii V. Nakariakov – Engineer (tel.: +007 342 216 54 92, e-mail: nakariakov.ev@gmail.com).

Левин Лев Юрьевич (Author ID in Scopus: 16407072500) – доктор технических наук, заведующий отделом аэрологии и теплофизики (тел.: +007 342 216 09 69, e-mail: aerolog_lev@mail.ru).
Семин Михаил Александрович – научный сотрудник, кандидат технических наук (тел.: +007 342 216 54 92, e-mail: mishkasemin@gmail.com). Контактное лицо для переписки.
Клюкин Юрий Андреевич – ведущий инженер (тел.: +007 342 216 54 92, e-mail: aeroyuri@gmail.com).
Накаряков Евгений Вадимович – инженер (тел.: +007 342 216 54 92, e-mail: nakariakov.ev@gmail.com).

Introduction

Construction and commissioning of production facilities of Usolskii potash plant is carried out on Palasherskii and part of Balakhontsevskii area of Verkhnekamskoie potassium and magnesium salts deposit. Opening a mine field at the first stage is carried by two shafts located in the center of the mine field. At the initial stage of pit bottom`s construction sinking cross slit between shafts providing cross-ventilation of the mine through the work of the main ventilation is going.

According to the schedule of mining completion of sinking cross slit between shafts falls for the period of negative outside temperatures when weather conditions cause a significant impact of the natural draft on air distribution [1]. In this case the predicted natural draft will be directed against the airflow rate envisaged the temporary scheme of mine ventilation and could have a significant negative impact on the formation of a sustainable mode of ventilation.

The study of transient processes occurring in the mine ventilation network directly after sinking cross slit between shafts in the cold season allows to develop technical solutions for the organization of a sustainable mode of ventilation in the initial stage of pit bottom`s construction.

Statement of the problem

The mine ventilation network of Usolskii potash plant during sinking cross slit between shafts is schematically shown in Fig. 1.

Ventilation network consists of a cage and skip shafts, cross slit between shafts and metal vent-tubing delivering fresh air from the site of cage shaft to cross slit between shafts. Vent-tubing has a diameter of 900 mm. Airflow is provided by tunneling fan VCP-16M installed at the site cage shaft. When constructing a model assumed that artificial ventilation of skip shaft before sinking cross slit between shafts is not carried.

The haulage roadway into two volumes is deleted (Fig. 1), which corresponds to the time of completion of sinking cross slit between shafts. Then an interaction of air masses around the considered volume of mine ventilation network model begins.

We analyze the worst case – the air temperature on the surface is equal to the temperature of the coldest five days for the region according to Building Codes and Regulations 23-01-99 "Building climatology" [2] and equal to –36 °C.

Since at the time of sinking cross slit between shafts there is no working at skip shaft and artificial ventilation is not carried, inside air temperature at the initial time taken everywhere equal to the surface air temperature. The choice of the initial condition is substantiated by absence of skip shaft seal, which causes an immersion cooler air mass from the surface into the shaft by a mechanism of convective mixing [3]. Fresh air temperature entering the mine from the vent-tubing is equal to + 4 °C .

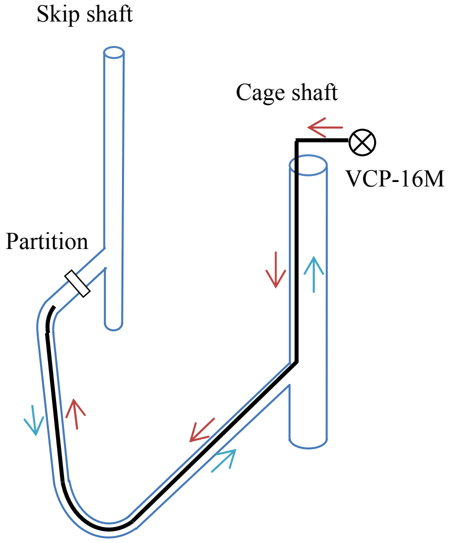


Fig. 1. Scheme of the calculation model

The airflow rate rate supplied to the mine through vent-tubing due to the work of the tunneling fan VCP-16M is equal to 21.3 m^3/s.

The purpose and structure of the study

The purpose of the study is the determination of aero- and thermodynamic parameters of transient processes occurring in the mine ventilation network after conclusion of sinking cross slit between shafts.

The subject of research is the impact of natural draft on the formation of the ventilation modes in the mine. It is assumed that in the worst case after the sinking cross slit between shafts in the cold season natural draft will be a determining factor in the distribution of airflow rate.

The study of air distribution in the mine ventilation network is made in several stages. At the first stage transient aero- and thermodynamic processes in the mine ventilation network were analysed within a one-dimensional approach. At the second stage numerical three-dimensional modeling of aero- and thermodynamic processes occurring in the mine was performed using means of software and computing system ANSYS. At the third stage of the study carried out a comparative analysis of the results of a one-dimensional analytic modeling and three-dimensional numerical modeling. Defined the parameters of the occurring upper-air processes which allow to execute the development of technical solutions for the organization of the mine ventilation scheme, taking into account the impact of natural draft arising during the cold season.

Mathematical model of ventilation network

As part of a one-dimensional approach the mine ventilation network of Usolskii potash plant shown in Fig. 1 can be represented as a graph [4], consisting of three edges – vent-tubing, cage and skip shafts combined with cross slit. (Fig. 2).

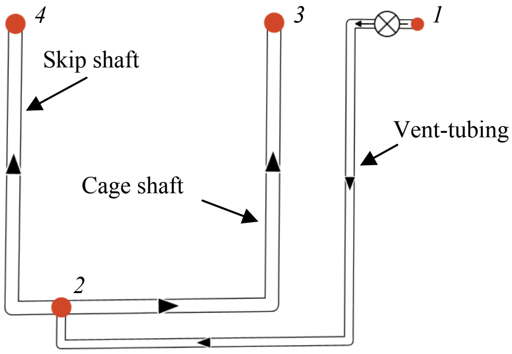


Fig. 2. Graph representations of the mine ventilation network: *1–4* – vertex of the graph

The following system of Kirchhoff's equations of 1st and 2nd kind is composed for a given graph of the main ventilation network [5]:

$$R_1Q_1|Q_1| + R_cQ_c|Q_c| + \frac{\rho L_1}{S_1}\frac{\partial Q_1}{\partial t} + \left(\frac{\rho L_c}{S_c} + \frac{\rho L_{cs}}{S_{cs}}\right)\frac{\partial Q_c}{\partial t} = H, \quad (1)$$

$$R_1Q_1|Q_1| + R_sQ_s|Q_s| + \frac{\rho L_1}{S_1}\frac{\partial Q_1}{\partial t} + \frac{\rho L_s}{S_s}\frac{\partial Q_s}{\partial t} = H, \quad (2)$$

$$Q_s + Q_c = Q_1. \quad (3)$$

Here Q_1, Q_s, Q_c – the airflow rate in the vent-tubing, skip and cage shafts respectively, m^3/s; R_1, R_s, R_c – aerodynamic resistance of skip shaft pipe, cage shaft and cross slit between shafts, N·s^2/m^8; L_1, L_s, L_c, – the length of the vent-tubing, cage and skip shafts, m; L_{cs} – the length of cross slit between shafts, m; S_1, S_s, S_c, S_{cs} – sectional area of the vent-tubing, cage and skip shafts and cross slit between shafts, m; ρ – air density, kg/m^3; H – fan head VCP-16M, Pa.

To write Kirchhoff equations of the 2nd kind (1) and (2) are usually formulated relatively the closed network loops [3, 5–7], assumed that the vertices 1, 3 and 4 are connected by the ribs with zero resistance and inertia simulating atmosphere [8].

The inertial terms are introduced in (1) and (2) based on research [8, 9].

At the initial time taken

$$Q_c = 0, \quad (4)$$

$$Q_c = Q_1 = 1277 \text{ m}^3/\text{min} = 21{,}3 \text{ m}^3/\text{s}. \quad (5)$$

The system (1)-(5) is also required to add the impact of natural draft. In the case where the value of the natural draft H_e does not exceed depression skip shaft,

$$H_e = gh(\rho_s - \rho_c) < H - R_1Q_1^2. \quad (6)$$

after opening the cross slit between shafts air from the vent-tubing gradually displace the cold air in the skip shaft, a natural draft in the ventilation loop formed by cage and skip shafts decreases by the law

$$H_e(t) = gh(\rho_s - \rho_c)\left(1 - \frac{1}{L_sS_s}\int_0^t Q_s(\tau)d\tau\right). \quad (7)$$

Equation (7) was obtained assuming the action of ideal displacement mechanism [10] and is valid until the time t' when all the skip shaft will be filled with warm air:

$$\frac{1}{L_sS_s}\int_0^{t'} Q_s(\tau)d\tau = 1. \quad (8)$$

points in time $t = 0$ and do not change in the calculation process. Change of the average air density $\rho_s(t)$ in the skip shaft with increasing temperature, and its approximation to the value of the air density ρ_c in the cage shaft is taken into account by means of the integral factor: it is equal to unity at the initial time when the natural draft is maximum and zero after a lapse of time t', when warm air completely replaces the cold air in the skip shaft and natural draft will be zero.

After a lapse of time t' air temperature everywhere in the mine ventilation network will be +4 °C, and the model value of natural draft – zero. Here is not considered hydrostatic air heating during lowering from surface to the cross slit between shafts.

If the value of natural draft exceeds skip shaft depression, after opening the cross slit skip shaft will be downcast ventilating shaft and natural draft until time t^*, when the cold stream goes through the cross slit in the cage shaft, will be constant and equal to

$$H_{\text{e}} = gh\left(\rho_{\text{s}} - \rho_{\text{c}}\right). \tag{9}$$

As before, the air density ρ_{s}, ρ_{c}, ρ_{l} in (9) are calculated for the points in time $t = 0$ and do not change in the calculation process. Natural draft (9) is defined for the ventilation loop formed by cage and skip shafts.

Further, after some time t^* natural draft will start to decrease by the law, analogous to (7):

$$\begin{gathered} H_{\text{e}} = gh\left(\rho_{\text{s}} - \rho_{\text{c}}\right) + \\ + \frac{gh}{L_{\text{c}} S_{\text{c}}}\left(\rho_{\text{c}} - \frac{\rho_{\text{s}} Q_{\text{s}} + \rho_{\text{l}} Q_{\text{l}}}{Q_{\text{s}} + Q_{\text{l}}}\right)\int_{t^*}^{t} Q_{\text{c}}(\tau)d\tau. \end{gathered} \tag{10}$$

Equation (10) holds true to the time t^{**}, when the whole cage shaft and cross slit filled with cold air:

$$\frac{1}{L_{\text{c}} S_{\text{c}}}\int_{t^*}^{t^{**}} Q_{\text{c}}(\tau)d\tau = 1. \tag{11}$$

In this case air temperatures in cage and skip shafts will always be different because the cold air coming from the skip shaft, mixed in the cross slit with warm air from the ventilation tubbing, further mixed air stream goes to cage shaft. Therefore at time t^{**}, when the whole cage shaft and the cross slit is filled with cold air, the quantity of natural draft is equal to

$$H_{\text{e}} = gh\left(\rho_{\text{s}} - \frac{\rho_{\text{s}} Q_{\text{s}} + \rho_{\text{в}} Q_{\text{l}}}{Q_{\text{s}} + Q_{\text{l}}}\right). \tag{12}$$

Natural draft calculated for the ventilation loop formed by the ventilation tubbing and cage shaft at an interval of time $\left[0, t^{**}\right]$ equal to

$$H_{\text{e}} = \theta\left(t - t^*\right)\frac{gh}{L_{\text{c}} S_{\text{c}}}\left(\rho_{\text{l}} - \frac{\rho_{\text{s}} Q_{\text{s}} + \rho_{\text{l}} Q_{\text{l}}}{Q_{\text{s}} + Q_{\text{l}}}\right)\int_{t^*}^{t} Q_{\text{c}}(\tau)d\tau \tag{13}$$

where θ – Heaviside function.

Natural draft calculated for the ventilation loop formed by the ventilation tubbing and skip shaft at an interval of time $\left[0, t^{**}\right]$ is constant and equal to

$$H_{\text{e}} = gh\left(\rho_{\text{s}} - \rho_{\text{c}}\right). \tag{14}$$

In the studied problem the projected natural draft (about 800 Pa) exceeds skip shaft depression (about 10 Pa) at the initial time. Therefore the system of equations (1)-(3), solved on the time interval $\left[0, t^{**}\right]$, It must be supplemented by a term that takes into account natural draft of the form (13)

$$\begin{gathered} R_{\text{l}} Q_{\text{l}}^2 + R_{\text{c}} Q_{\text{c}}^2 + \frac{\rho L_{\text{l}}}{S_{\text{l}}}\frac{\partial Q_{\text{l}}}{\partial t} + \\ + \left(\frac{\rho L_{\text{c}}}{S_{\text{c}}} + \frac{\rho L_{\text{cs}}}{S_{\text{cs}}}\right)\frac{\partial Q_{\text{c}}}{\partial t} = H + \\ + \theta\left(t - t^*\right)\frac{gh}{L_{\text{c}} S_{\text{c}}}\left(\rho_{\text{l}} - \frac{\rho_{\text{s}} Q_{\text{s}} + \rho_{\text{l}} Q_{\text{l}}}{Q_{\text{s}} + Q_{\text{l}}}\right)\int_{t^*}^{t} Q_{\text{c}}(\tau)d\tau. \end{gathered} \tag{15}$$

$$\begin{gathered} R_{\text{l}} Q_{\text{l}}^2 + R_{\text{s}} Q_{\text{s}}^2 + \frac{\rho L_{\text{l}}}{S_{\text{l}}}\frac{\partial Q_{\text{l}}}{\partial t} + \\ + \frac{\rho L_{\text{s}}}{S_{\text{s}}}\frac{\partial Q_{\text{s}}}{\partial t} = H - gh\left(\rho_{\text{s}} - \rho_{\text{l}}\right), \end{gathered} \tag{16}$$

$$Q_{\text{s}} + Q_{\text{c}} = Q_{\text{l}}. \tag{17}$$

Direction of airflow rate under $t \in \left[0, t^*\right]$ is also taken into account in (15)-(17).

Exact analytical solution of Volterra integral-differential equations system of the 2nd kind (15)-(17) with the initial conditions (4)-(5) can not be obtained. Therefore, to solve this problem, we introduce the assumption about insignificance of change the airflow rate in the vent-tubing after opening the cross slit. The introduction of such assumptions caused by the fact that depression a vent-tubing is about 8000 Pa, which is much higher than the predicted value of natural draft.

$$Q_{\text{l}}(t) = Q_{\text{l}}^{(0)}, \tag{18}$$

where $Q_{\text{l}}^{(0)}$ – the airflow rate in the vent-tubing at the initial time, m^3/s.

Analytical study of non-stationary air distribution

Consider the system of equations (15)-(17) under $t \in \left[0, t^*\right]$.

In this case the number of unknowns is reduced from 3 to 2, and the system of equations (15)-(17) is reduced to the following system of two equations:

$$\begin{gathered} R_{\text{s}} Q_{\text{s}}^2 + R_{\text{c}} Q_{\text{c}}^2 + \frac{\rho L_{\text{s}}}{S_{\text{s}}}\frac{\partial Q_{\text{s}}}{\partial t} + \\ + \left(\frac{\rho L_{\text{c}}}{S_{\text{c}}} + \frac{\rho L_{\text{cs}}}{S_{\text{мс}}}\right)\frac{\partial Q_{\text{c}}}{\partial t} = gh\left(\rho_{\text{s}} - \rho_{\text{c}}\right). \end{gathered} \tag{19}$$

$$Q_{\mathrm{s}} + Q_{\mathrm{l}}^{(0)} = Q_{\mathrm{c}}. \tag{20}$$

As a result of solving the equation system (19)-(20) we obtain the following expression for non-stationary airflow rate in the main ventilation network under $t \in \left[0, t^{*}\right]$:

$$Q_{\mathrm{c}}(t) = \frac{Q_{\mathrm{l}}^{(0)} R_{\mathrm{s}}}{R_{\mathrm{c}} + R_{\mathrm{s}}} + \frac{b}{R_{\mathrm{c}} + R_{\mathrm{s}}} \tanh\left[\frac{bt}{a} - \operatorname{arctanh}\left(\frac{Q_{\mathrm{l}}^{(0)} R_{\mathrm{c}}}{b}\right)\right], \tag{21}$$

$$Q_{\mathrm{s}}(t) = -\frac{Q_{\mathrm{l}}^{(0)} R_{\mathrm{c}}}{R_{\mathrm{c}} + R_{\mathrm{s}}} + \frac{b}{R_{\mathrm{c}} + R_{\mathrm{s}}} \tanh\left[\frac{bt}{a} - \operatorname{arctanh}\left(\frac{Q_{\mathrm{l}}^{(0)} R_{\mathrm{c}}}{b}\right)\right], \tag{22}$$

$$a = \frac{\rho_{\mathrm{s}} L_{\mathrm{s}}}{S_{\mathrm{s}}} + \frac{\rho_{\mathrm{c}} L_{\mathrm{c}}}{S_{\mathrm{c}}} + \frac{\rho_{\mathrm{cs}} L_{\mathrm{cs}}}{S_{\mathrm{cs}}},$$

$$b = \sqrt{gh\left(\rho_{\mathrm{s}} - \rho_{\mathrm{c}}\right)\left(R_{\mathrm{s}} + R_{\mathrm{c}}\right) - R_{\mathrm{s}} R_{\mathrm{c}} Q_{\mathrm{l}}^{(0)2}},$$

$$Q_{\mathrm{l}} = Q_{\mathrm{l}}^{(0)}. \tag{23}$$

At the moment t^{*}, determined from the equation

$$1 = \frac{1}{L_{\mathrm{cs}} S_{\mathrm{cs}}} \int_{0}^{t^{*}} Q_{\mathrm{c}}(\tau) d\tau = \frac{Q_{\mathrm{l}}^{(0)} R_{\mathrm{s}} t^{*}}{R_{\mathrm{c}} + R_{\mathrm{s}}} + \frac{a}{R_{\mathrm{c}} + R_{\mathrm{s}}} \ln\left\{\cosh\left[\frac{bt^{*}}{a} - \operatorname{arctanh}\left(\frac{Q_{\mathrm{l}}^{(0)} R_{\mathrm{c}}}{b}\right)\right]\right\} - \frac{a}{R_{\mathrm{c}} + R_{\mathrm{s}}} \ln\left\{\cosh\left[-\operatorname{arctanh}\left(\frac{Q_{\mathrm{l}}^{(0)} R_{\mathrm{c}}}{b}\right)\right]\right\}, \tag{24}$$

airflow rate values will serve as the initial conditions for solving a system of integral-differential equations (15)-(17) under $t \in \left[t^{*}, t^{**}\right]$.

Solution of the transcendental equation (24) relatively t^{*} allows to determine the point in time when the cold air stream falls into the cage shaft. For the parameters of workings of the mine ventilation network of Usolskii potash plant (Table 1) this time is $t^{*} = 31.5$ s. Airflow rates at a given time based on the expressions (21)-(23) are equal $Q_{\mathrm{c}} = 238{,}8\ \mathrm{m}^{3}/\mathrm{s}$, $Q_{\mathrm{s}} = 217{,}5\ \mathrm{m}^{3}/\mathrm{s}$, $Q_{\mathrm{l}} = 21{,}3\ \mathrm{m}^{3}/\mathrm{s}$.

Model aerodynamic resistances of shafts are calculated based on the research results [11, 12].

Table 1

The geometrical and physical parameters of the workings in the ventilation network model

Characteristic	Value			
	Skip shaft	Cage shaft	Ventilation tubbing	Cross slit
Length, m	428	428	720	300
Area, m^2	37	50	2.5	15.5
Aerodynamic resistance, $N \cdot \mathrm{s}^2/\mathrm{m}^8$	0.01	0.004	17.4	0.0065

Fig. 3 shows the dependence of airflow rate in cage and skip shaft versus time for the time interval of $t \in \left[0, t^{*}\right]$.

To the moment $t^{*} = 31.5$ s given curves are already quite close to its asymptote.

System of equations (15)-(17) for the time interval of $t \in \left[t^{*}, t^{**}\right]$ can be written as

$$R_{\mathrm{s}} Q_{\mathrm{s}}^{2} + R_{\mathrm{c}} Q_{\mathrm{c}}^{2} + \frac{\rho_{\mathrm{s}} L_{\mathrm{s}}}{S_{\mathrm{s}}} \frac{\partial Q_{\mathrm{s}}}{\partial t} + \left(\frac{\rho_{\mathrm{c}} L_{\mathrm{c}}}{S_{\mathrm{c}}} + \frac{\rho_{\mathrm{c}} L_{\mathrm{cs}}}{S_{\mathrm{cs}}}\right) \frac{\partial Q_{\mathrm{c}}}{\partial t} = gh\left(\rho_{\mathrm{s}} - \rho_{\mathrm{c}}\right)\left(1 - \frac{1}{L_{\mathrm{c}} S_{\mathrm{c}}} \int_{t^{*}}^{t} Q_{\mathrm{c}}(\tau) d\tau\right), \tag{25}$$

$$Q_{\mathrm{s}} + Q_{\mathrm{l}}^{(0)} = Q_{\mathrm{c}}. \tag{26}$$

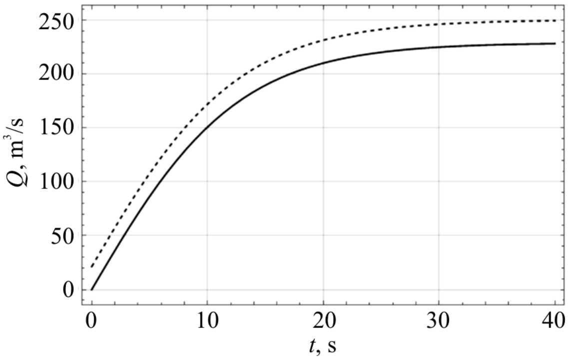


Fig. 3. Changing the airflow rate in cage (⋯⋯⋯) and skip (——) shafts versus time

Getting the exact solution of the system (25)-(26) is difficult because of its nonlinearity. To study the asymptotic behavior of solution in time area t^{*} we fix values of the aerodynamic resistances in the equation (25). Then the approximate solution of the system (25)-(26) for the time interval of $t \in \left[t^{*}, t^{**}\right]$ has the form

$$Q_{\mathrm{c}} = Q_{\mathrm{c}}(t^{*}) \cos\left(ct - ct^{*}\right), \tag{27}$$

$$Q_{\mathrm{s}} = Q_{\mathrm{s}}(t^*)\cos\left(ct - ct^*\right), \qquad (28)$$

$$c = \sqrt{\frac{gh\left(\rho_{\mathrm{s}} - \rho_{\mathrm{c}}\right)}{L_{\mathrm{c}} S_{\mathrm{c}} a}},$$

$$a = \frac{\rho_{\mathrm{s}} L_{\mathrm{s}}}{S_{\mathrm{s}}} + \frac{\rho_{\mathrm{c}} L_{\mathrm{c}}}{S_{\mathrm{c}}} + \frac{\rho_{\mathrm{cs}} L_{\mathrm{cs}}}{S_{\mathrm{cs}}},$$

$$Q_1 = Q_1^{(0)}. \qquad (29)$$

Thus, when $t \in \left[t^*, t^{**}\right]$ natural draft will be gradually weaken, and airflow rates in theshafts will first briefly increase (under the influence of inertial forces) and then decrease to values corresponding to the stationary mode of ventilation. In the stationary mode of ventilation cage shaft air temperature and hence the natural draft will be determined by the ratio of airflow rates in the skip shaft and vent-tubing:

$$H_{\mathrm{e}} = gh\left(\rho_{\mathrm{s}} - \frac{\rho_{\mathrm{s}} Q_{\mathrm{s}} + \rho_1 Q_1}{Q_{\mathrm{s}} + Q_1}\right). \qquad (30)$$

Airflow rates will satisfy the equations

$$R_{\mathrm{s}} Q_{\mathrm{s}}^2 + R_{\mathrm{c}} Q_{\mathrm{c}}^2 = gh\left(\rho_{\mathrm{s}} - \frac{\rho_{\mathrm{s}} Q_{\mathrm{s}} + \rho_1 Q_1^{(0)}}{Q_{\mathrm{s}} + Q_1^{(0)}}\right), \qquad (31)$$

$$Q_{\mathrm{s}} + Q_{\mathrm{c}} = Q_1^{(0)}. \qquad (32)$$

Для параметров рассматриваемой задачи по Airflow rates at the time $t \to \infty$ according to parameters of the problem are equal: $Q_{\mathrm{c}} = 115.7$ m^3/s, $Q_{\mathrm{s}} = 94.4$ m^3/s.

Fig. 4 shows the dependence of airflow rates in cage and skip shafts versus time for the time interval of $t \in \left[0, t^{**}\right]$, also airflow rates in cage and skip shafts within the time $t \to \infty$. Places of solutions conjunction are marked by points (21)-(22) and (27)-(29) for different time intervals.

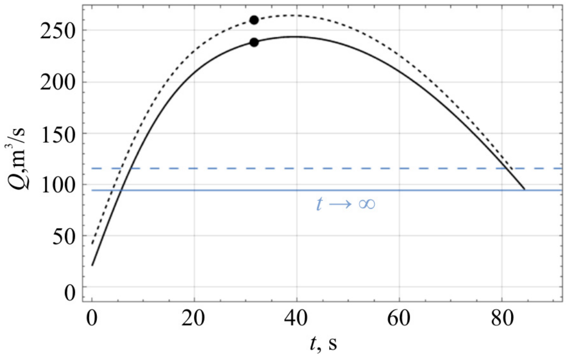


Fig. 4. Changing the airflow rate rate in cage (·········) and skip (——) shafts versus time; horizontal lines mark the stationary airflow rate within the time $t \to \infty$

Resultant curves for the time interval of $t \in \left[t^*, t^{**}\right]$ allow analyze the dynamics of the air distribution in the mine ventilation network only precisely enough for the time of not more than 60 seconds. Henceforth airflow rates begin to differ greatly from the airflow at $t^* = 31.5$ s, which leads to error growth (acceptance of the hypothesis of the fixed values of of the aerodynamic resistances in the equation (25)). This is evidenced by the fact that the time dependence of airflow rates (27)-(29) not smoothly mate with the solution at infinity (Fig. 4).

Airflow rates obtained from the system solutions (31)-(32) when $t \to \infty$, depend on the air temperature on the surface according to the curve shown in Fig. 5.

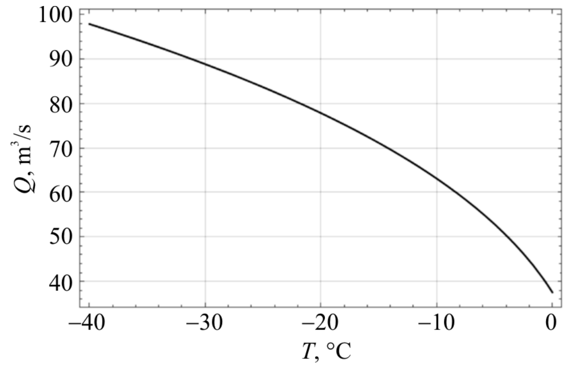


Fig. 5. Airflow rate in cage shaft when $t \to \infty$ depending on the temperature at the surface

One of the possible measures to reduce values of airflow rate in the mine ventilation network and the effect of the natural draft is overlapping cage shaft [13]. Let us analyze the impact of the aerodynamic resistance of the cage shaft at the stationary solution of the system (31)-(32). Fig. 6 shows the dependence of the air flow rate in cage shaft from the aerodynamic resistance of this shaft.

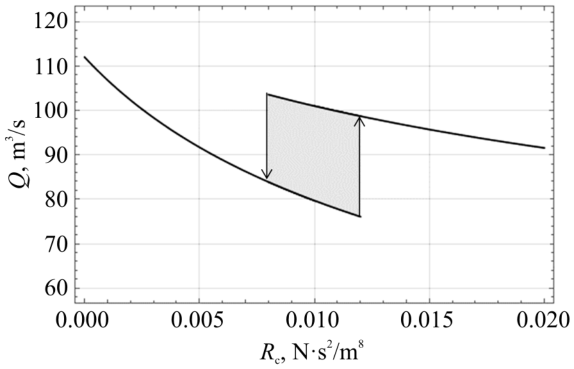


Fig. 6. Airflow rate in the cage shaft when $t \to \infty$ depending on the aerodynamic resistance of the shaft

With an increase in the aerodynamic resistance in cage shaft airflow rate decreases in the main ventilation network. When the aerodynamic resistance of the cage shaft begins to exceed aerodynamic resistance of the skip shaft

$$R_c > R_s = 0{,}01\ \mathrm{H\cdot s^2/m^8}, \qquad (33)$$

air distribution becomes unstable, "overturns ", at the same time the airflow rate "jumps" from one to another curve. Instability is caused by the fact that with an increase in the aerodynamic resistance of the cage shaft, the movement of air in the ventilation network counterclockwise (air in the cage shaft) is more energy-consuming than the clockwise (air in the skip shaft), shown in Fig. 7.

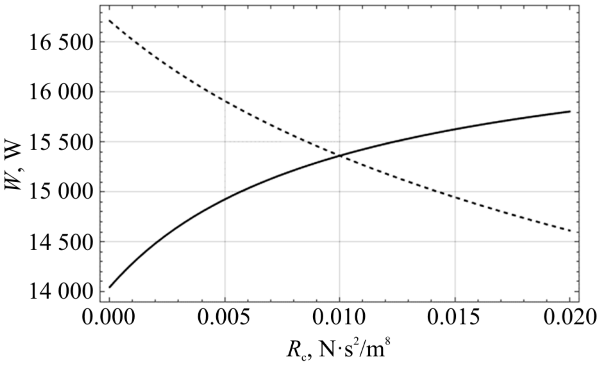


Fig. 7. Power spent on airing of the mine ventilation network by natural draft, for clockwise ventilation mode (·········· – skip shaft is a vent) for counterclockwise ventilation mode (——— – skip shaft is air supply)

Should be noted that overturning of the air stream does not occur immediately after the condition (33), but only after the power difference will be higher than the power of natural draft $gh(\rho_s - \rho_c)\min(Q_s, Q_c)$. Therefore a function of the airflow from the resistance is represented as a hysteresis.

After closing the cage shaft a stable mode of ventilation is formed that persists in this form after the cage shaft open again. Obtained when $t \to \infty$ airflow rates in the skip shaft depend on the temperature on the surface according to the curve shown.

At this stage of the construction of the mine implementation of presented activity can be complicated by the inability to provide the required tightness of estuary of the cage shaft or its conjugation with a transport horizon. In this case established mode of the mine ventiolation due to the impact of natural draft can not be changed by means of negative and positive regulation.

Further because of the known processes of convective airflow separation on the perimeter of shafts [3, 8, 14], in the present study the correctness of the application of the one-dimensional approach for the study of transient processes in mine ventilation network is being verified. This is done using a three-dimensional numerical simulation by methods of computational fluid dynamics and gas.

Numerical simulation of air distribution in three-dimensional setting

To verify the correctness of one-dimensional approach to the modeling of transient processes in the mine ventilation network of Usolskii potash plant during sinking cross slit between shafts and to clarify the distribution of air velocities in the volume of the mine ventilation network, a series of calculations using software and computing system ANSYS, Fluent module was carried out. Fig. 8 presents the computational domain of the mine ventilation network.

On the presented computational domain unstructured finite element grid with tetrahedral elements in the inner zone and prismatic elements on the border with the walls (boundary layer) is constructed. Several finite element grids with a different number and size of items were constructed to verify the independence of the solution on the method of finite element decomposition of the computational domain. It is studied the convergence of the solution with grinding the finite element grid.

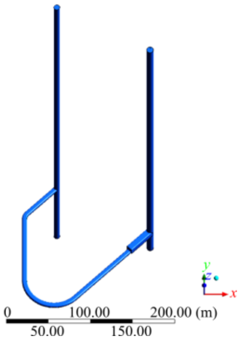


Fig. 8. The computational domain of the mine ventilation network

For the calculation applied the finite volume method with a consistent in time correction of velocity – pressure fields [16]. It is used the model of the turbulence standard k-epsilon with scalable wall functions [16, 17]. The roughness of the walls of the mine workings is given in the form of an additional logarithmic term in the wall function for the dimensionless air velocity [18].

In the simulation of natural draft is accepted that the air density depends on the temperature according to the ideal gas law (Mendeleev–

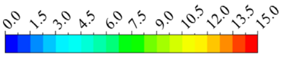
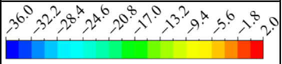
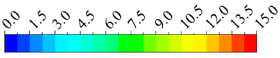
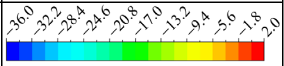
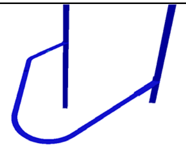
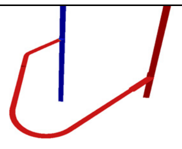
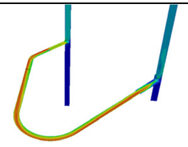
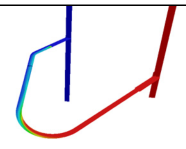
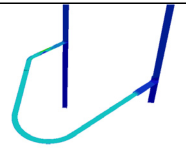
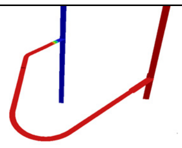
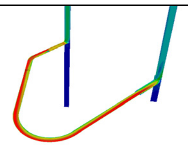
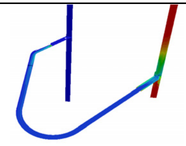
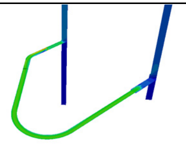
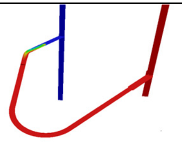
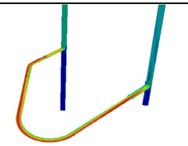
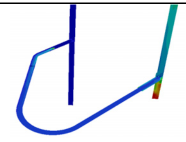
Clapeyron equation) [19]. Under this approach the air density depends on the temperature and absolute pressure.

Table 2 represents obtained as a result of numerical simulation the temperature distribution and air velocity in the middle sections of the cage and skip shafts and the cross slit at different moments after opening the cross slit between shafts.

Table 2 shows that the heat transfer in the three-dimensional model is carried out mainly through a process of ideal displacement of warm air by cold. The process of thermal diffusion of flows is weakly expressed because of the smallness of the typical transverse dimensions of the mine workings in comparison with their characteristic lengths.

Table 2

The distribution of temperature and air velocity in the middle sections of the cage and skip shafts and the cross slit at different moments

Time, s	Velocity distribution, m/s	Tempersature distribution, °C	Time, s	Velocity distribution, m/s	Tempersature distribution, °C
					
0			20		
5			40		
10			60		

Comparative analysis of numerical simulation results and analytical calculations

Table 2 shows that until time t = 40 s airflow passing through the ventilation network rate increases under the influence of natural draft and reaches its peak, equal to 284 m^3/s for the cross slit and the cage shaft; 262 m^3/s for the skip shaft. At the moment t = 30 s the cold air stream reaches the cage shaft. This fact is in good agreement with the results of the one-dimensional theoretical analysis.

Subsequently cold air stream begins to climb up the cage shaft, a result of which the impact of natural draft weakens. However between the weakening of the influence of natural draft and a reduction of air flow in the shafts there is a long delay in comparison with the results obtained in the one-dimensional model. This is related to the lack of consideration air compressibility in one-dimensional setting [20].

Fig. 9 shows the dependence of the air velocity in cage shaft resulting from the one-dimensional theoretical analysis and the three-dimensional numerical simulation.

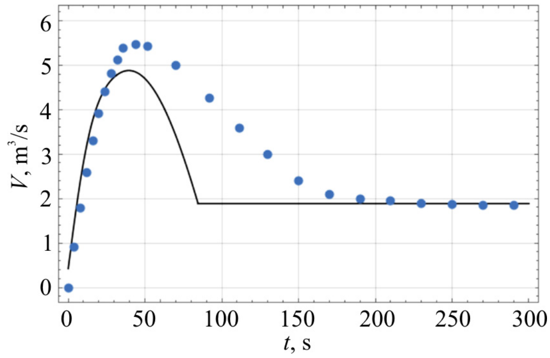


Fig. 9. Changing the air velocity in the cage shaft as the results of: —— – theoretical analysis; ● – numerical simulation

Based on these studies we can conclude that the results of one-dimensional and three-dimensional simulation converge well on the interval $t \in \left[0, t^*\right]$ and when $t \to \infty$. In addition, the three-dimensional model allows us to determine the time to stationary mode of ventilation.

Conclusion

This work investigates the influence of natural draft on the air distribution in the main distribution network of Usolskii potash plant after completion of sinking cross slit between shafts in cold period. We constructed one-dimensional mathematical model of airflow after sinking cross slit between shafts considering the time-varying effect of natural draft, as well as the inertia of the air. On the basis of a mathematical model approximate analytical solution of the problem of non-stationary air distribution is obtained.

We consider several scenarios of unstable mine ventilation depending on the natural draft, we determined a mechanism of stability loss of the airflow and ventilation mode changes after overlapping shaft neutral by ventilate.

We made a comparison of the data obtained in one-dimensional settings with the results of numerical three-dimensional simulation of airflow with different thermodynamic parameters in complex software ANSYS. It was found matching the results of the analytical one-dimensional and numerical three-dimensional simulation for the initial time period and after establishment of the stationary air distribution. Compliance is ensured by the fact that the heat transfer in the initial period of time in three-dimensional model is carried out mainly through a process of ideal displacement of warm air by cold, thermal diffusion process flow is weakly expressed because of the smallness of the typical transverse dimensions of the mine workings in comparison with their characteristic lengths. In the time interval characterized by the transition from peak airflow rates to the stationary values there is a significant mismatch of data the cause of which is the lack of consideration of the air compressibility in solving the problem in one-dimensional setting.

The above mismatch influences on the predicted time transient processes flowing, but do not change value arising thermal depressions and corresponding airflow rates, that allow use a one-dimensional approach to the development of technical solutions for the organization of the design ventilation mode.

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