MINING SCIENCE AND TECHNOLOGY (RUSSIA)
ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ
2023;8(2):150–161
eISSN 2500-0632
https://mst.misis.ru/

SAFETY IN MINING AND PROCESSING INDUSTRY AND ENVIRONMENTAL PROTECTION

Research paper

https://doi.org/10.17073/2500-0632-2022-10-13
УДК 622.4

Parameterization of a ventilation network model for the analysis of mine working emergency ventilation modes

M.O. Perestoronin ✉, **O.S. Parshakov**, **M.D. Popov**
Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation
✉ *per.maks1m.97@gmail.com*

Abstract
Digital simulation of mine fires and explosions is an important stage in the process of developing technical solutions and measures aimed at improving the safety of personnel involved in underground mining. Correct simulation results determine the effectiveness of decisions in the event of an actual emergency situation. In this regard, due attention should be paid to each stage of the simulation, and especially to the initial stage of model parameterization. This study formulates a general principle for determining the parameters of mine fire and explosion models, in order to assess their development using the AeroNetwork analytical package. Such parameters in the event of a fire are heat and gas (afterdamp) releases. In the event of an explosion, excessive pressure at the shock front in the explosion origin. It has been established that when simulating a fire, it is advisable to use equivalent heat and gas releases determined by the content of combustible components in the combustion origin. In the event of burning mining equipment, these parameters can be calculated on the basis of the technical characteristics of a machine. Furthermore, when simulating an unauthorized explosion of explosives, the excess pressure determined by the dimensionless length of the active combustion area is calculated taking into account the weight and specific heat of an explosive, as well as the geometric parameters of a mine working. When simulating an explosion of a methane-air mixture (firedamp), the excess pressure is calculated taking into account the gas content of rocks in terms of free combustible gases, the length of a blast cut, the size of the area of increased fracturing, and the lower explosive limit of methane. Based on the proposed principle of the parameterization of emergency models, as an example, a model of fire and explosion development in existing extended dead-end workings (more than 1000 m long) passing coaxially to each other at different heights was developed. The numerical simulation of different emergency situations in workings was carried out, taking into account performing mining in difficult mining conditions.

Keywords
mine, underground fire, explosion, emergency, shock wave, simulation, AeroNetwork, parameterization, safety

Acknowledgments
The study was carried out with the financial support of the Russian Science Foundation as part of Project No. 20-35-90072.

For citation
Perestoronin M.O., Parshakov O.S., Popov M.D. Parameterization of a ventilation network model for the analysis of mine working emergency ventilation modes. *Mining Science and Technology (Russia)*. 2023;8(2):150–161. https://doi.org/10.17073/2500-0632-2022-10-13

ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Параметризация модели вентиляционной сети при анализе аварийных режимов проветривания систем горных выработок

М.О. Пересторонин ✉, **О.С. Паршаков**, **М.Д. Попов**
Горный институт Уральского отделения Российской академии наук (ГИ УрО РАН), г. Пермь, Российская Федерация
✉ *per.maks1m.97@gmail.com*

Аннотация
Численное моделирование развития рудничных пожаров и взрывов является важным этапом в процессе разработки технических решений и мероприятий по повышению безопасности персонала, задействованного на подземных работах. От корректности результатов моделирования зависит, насколько принятые решения будут эффективны в случае возникновения реальной аварийной ситуации. В связи с этим долж-

ное внимание необходимо уделять каждой стадии моделирования, и в особенности начальной – стадии параметризации модели. В настоящем исследовании сформулирован общий принцип определения параметров моделей рудничных пожаров и взрывов для оценки их развития при помощи аналитического комплекса «АэроСеть». Такими параметрами в случае пожара являются тепло- и газовыделения, а в случае взрыва – избыточное давление на фронте ударной волны в очаге взрыва. Установлено, что при моделировании пожара целесообразно использовать эквивалентные тепло- и газовыделения, определяемые содержанием горючих компонентов в источнике горения. В случае горения горнопроходческой техники данные параметры возможно рассчитать на основании технических характеристик машины. В свою очередь, при моделировании несанкционированного взрыва взрывчатых материалов избыточное давление, определяемое безразмерной длиной активного участка горения , рассчитывается с учетом массы и удельной теплоты сгорания взрывчатого вещества, а также геометрических параметров выработки. При моделировании взрыва метановоздушной смеси избыточное давление рассчитывается с учетом газоносности пород по свободным горючим газам, длины буровзрывной заходки, размеров области повышенного трещинообразования, а также нижнего предела взрываемости метана. На основании предлагаемого принципа параметризации аварийных моделей в качестве примера выполнена разработка модели развития пожара и взрыва в существующих протяженных тупиковых выработках (длиной более 1000 м), проходимых соосно друг другу на разных высотных отметках. Произведено численное моделирование различных аварийных ситуаций в выработках с учетом ведения горных работ в сложных горнотехнических условиях.

Ключевые слова
рудник, подземный пожар, взрыв, аварийная ситуация, ударная волна, моделирование, АэроСеть, параметризация, безопасность

Благодарности
Исследование выполнено при финансовой поддержке Российского научного фонда в рамках проекта № 20-35-90072.

Для цитирования
Perestoronin M.O., Parshakov O.S., Popov M.D. Parameterization of a ventilation network model for the analysis of mine working emergency ventilation modes. *Mining Science and Technology* (*Russia*). 2023;8(2):150–161. https://doi.org/10.17073/2500-0632-2022-10-13

Introduction

In accordance with Industrial Safety Law No. FZ-116, a mining enterprise is a hazardous production facility characterized by an increased risk of emergency. The issue of the safety of people is especially acute in dead-end underground workings under construction, which have only one emergency exit from a work area. For such dangerous working conditions, technical solutions and measures need to be developed, in order to ensure the safe evacuation of people and the effective conduct of mine rescue operations. At the same time, it is advisable to use the capabilities of numerical simulation for developing solutions and measures.

According to statistics [1, 2], mine fires and explosions are the most destructive and frequent accidents. Therefore, in order to develop optimal measures to improve the safety of miners, these particular emergency situations need to be predictable. However, adequate parameterization of such models is a highly complex task.

For instance, in terms of the spread of combustion products in mine workings, the issue of fire development simulation is covered in the studies [3–5]. A common drawback of the studies presented here and other existing studies in this field is that emergency heat and gas releases are considered without reference to a specific origin of combustion. As a rule, the abstract parameters that reflect the possible most unfavorable aerological and heat-and-gas-dynamic conditions are used as input data for simulation, such as 100 % gas release [6, 7] or 50 MW heat generation [8] in the case of a “severe” fire. This simplification is due to the significant complexity of calculating these parameters, since they can be determined only based on the results of full-scale experiments, such as in [9, 10], or in additional fire physical process simulation such as in [11].

Analytical calculation of heat and gas releases in the case of a fire, taking into account specific mining conditions is optimal. This approach allows for the adoption of adequate simulation parameters at relatively low labor costs. To date, since such analytical relationships are not available, and no methodology for calculating heat and gas releases from a mine fire has been developed, scientific research in this area is very relevant.

In turn, in the case of mine explosions, the studies of Abinov A.G., Vasenin I.M., Lukashov O.Yu., Paleev D.Yu., Plotnikov V.M. et al. should be mentioned. Their findings form the basis for the *Gas Dynamic Calculation Methodology*[1], currently used to

[1] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia “On implementing the “Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions” dated April 27, 2004, 16 p.

define the parameters of air shock waves generated by explosions in mines. This methodology introduces the concept of an "active combustion area". This is a mining area filled with an explosive mixture, and determines the initial excess pressure at the shock front in an explosion origin. However, the focus of the methodology on emergency calculations does the length of this area to be established without actually measured gaseousness (gas hazard) parameters of a mine working. In other words, this methodology does not answer the question of how to calculate the length of an active combustion area for a non-emergency working conditions. This requires evacuation, and for mine rescue measures to be developed in advance. In the event of an unauthorized explosion of explosives, the required length can be determined by the analytical relationships presented in [12]. However, in the event of an explosion of a methane-air mixture (firedamp), this question remains open and therefore requires investigation.

In connection with the above, and using the example of extensive dead-end workings at one of the Russian mines, this paper proposes a methodology for calculating the parameters of a mine fire and explosion development model in the AeroNetwork analytical software package. This is one of the main tools for solving problems in the field of mine ventilation and mine safety.

The findings of this study are expected to be useful not only for AeroNetwork users digitally simulating the development of accidents in mine workings, but also for other aerological safety specialists involved in calculating mine fires and explosions.

Subject of research

The research considers two extensive dead-end workings in a Russian mine. The workings were driven, in order to perform geological and geotechnical studies and to provide a ventilation connection between the mine shafts. A schematic diagram of the spatial location of the workings is shown in Fig. 1.

The workings involved can be characterized by the following routing features and driving conditions:

– the workings are being driven simultaneously towards Shaft No. 2;

– working No. 1 is located at a depth of 1750–1850 m (ascending slope 3° towards Shaft No. 2), while a depth of working No. 2 is 1950 m (with no gradient);

– the design length of the workings is 1840 m; No. 1 is curvilinear, while No. 2 is rectilinear with a minimum number of turns;

– the cross-sectional shape of the workings is arched, the cross-sectional area is 17.8 m^2 in drivage and 17.0 m 2 in clear;

– a drilling and blasting complex used to drive the workings consists of: an Epiroc Boomer 282 drilling rig, an Epiroc ST-1030 bucket LHD, and a Sandvik TH 320 dump truck;

– a ventilation system for ventilating the workings consists of: 3 fans on the surface, 5 flexible ducts in Shaft No. 1, 2 ventilation chambers, 4 underground booster fans, and 2 rigid ducts in the workings (Fig. 2);

– the intake air consumption in each working is 20 m^3/s; the booster fan (located in ventilation chamber) performance is 19.3 m^3/s; the booster fan (located in the niche) performance is 17.2 m^3/s; the air consumption at the face is 15.1 m^3/s;

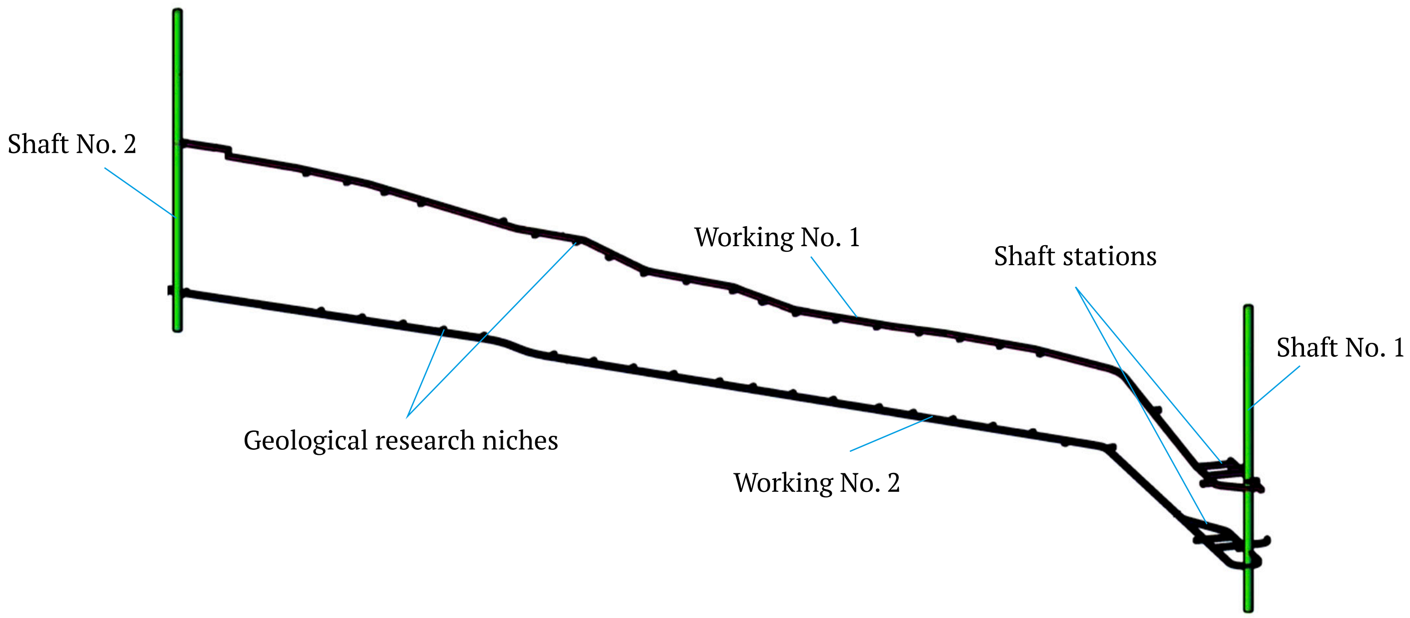

Fig. 1. Schematic diagram of the spatial location of the workings

– the average temperature of the intact rock mass surrounding working No. 1 is 44.5 °C, and that for working No. 2, 46.6 °C;

– at an outdoor temperature of 21.0° C, as a result of hydrostatic compression, friction, and heat exchange, the temperatures of the intake air in workings No. 1 and No. 2 are 33.3 and 34.4 °C, respectively.

Fire development model parameterization

The most dangerous endogenous fire is one caused by a fire in process vehicles. Such a fire is characterized by rapid development and accompanied by significant heat and gas releases. In this regard, in order to predict an emergency air-gas dynamic situation in workings, a fire of a vehicle containing the maximum fire load should be taken into account.

The main fire load of a mining vehicle can be ascribed to fuel, luboil, and rubber [13]. The content of other combustible components is negligible, so their impact on the development of fire can be neglected. An approximate fire load of a vehicle can be determined using its technical cer-tificate. For instance, the fuel tank volume reflects fuel content, the volume of the hydraulic system reflects the luboil content, and the tire size reflects the rubber content.

The key parameters of a mine working fire development model are specific heat and gas releases. These parameters are time-varying, since a fire proceeds in several stages with differing combustion intensity [14]. In order to simplify the simulation, equivalent values should be set throughout all stages of a fire (Fig. 3).

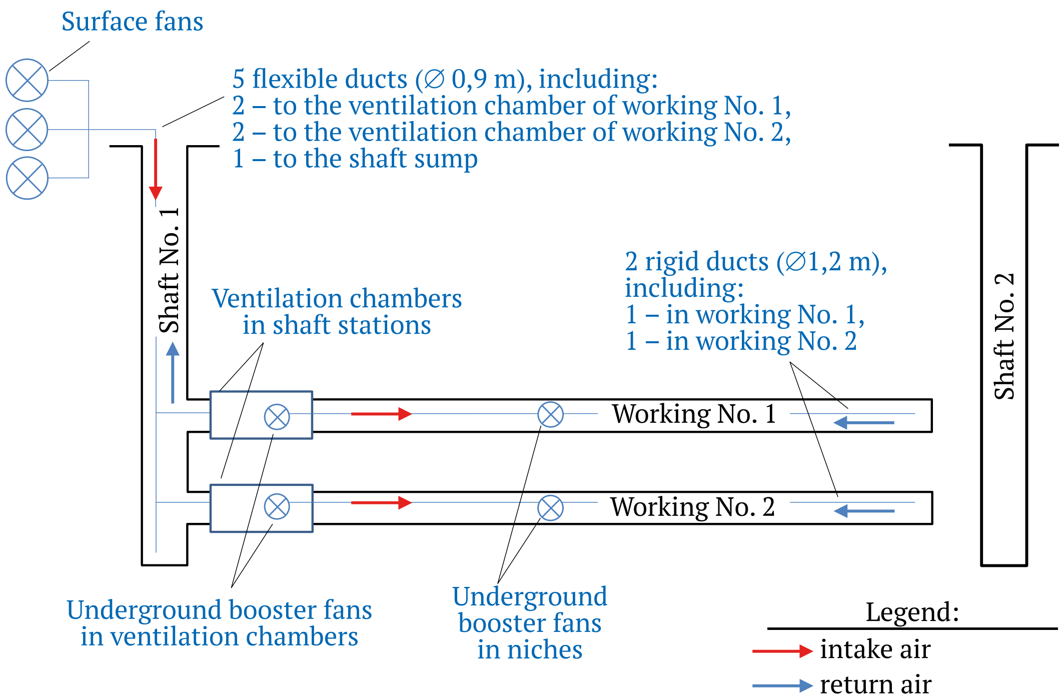

Fig. 2. Workings ventilation schematic diagram

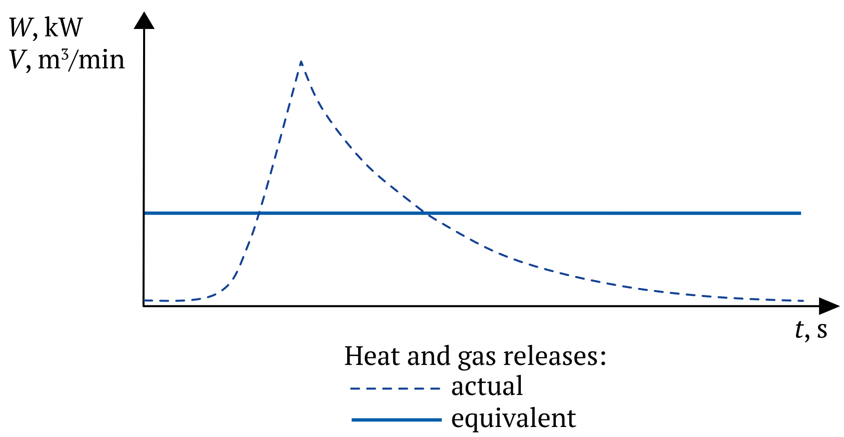

Fig. 3. Principal presentation of equivalent heat and gas releases during the combustion of vehicles

In order to calculate the maximum heat releases, kW, from the combustion of a certain fuel component at some instant, a well-known formula can be used [15]:

$$W_i = \psi_i Q_i \eta, \quad (1)$$

where ψ_i is mass rate of burnout of a material of the fire load at a time, kg/s ($\psi_i = \psi_{spec\,i}\, S_i$, where $\psi_{spec\,i}$ is specific burnout rate of a material, kg/(s·m^2), S_i is combustion area at a time, m^2); Q_i is lower calorific value of a material, kJ/kg; η is combustion rate factor (assumed to be 0.85 in accordance with [15]).

In this case, the burnout time (s) of the combustible load is determined by the formula:

$$t_{spec\,i} = \frac{m_i \eta}{\psi_{spec\,i} S_i}, \quad (2)$$

where m_i s mass of fuel component, kg.

For expression (2), it is proposed to take, the surface area of a sphere as a combustion area, into which the entire mass of the fire load for each component is inscribed. Then the equivalent of heat releases, kW, from a burning vehicle throughout all stages of a fire will be of a certain average value. This can be determined by summing up the average heat releases from each of the components:

$$W_{spec} = \sum_i W_{spec\,i}. \quad (3)$$

At the same time, the average value of heat generation, kW, from each of the components can be determined based on the maximum burning time of a vehicle t_{max}. This corresponds to the time of complete burnout of the last burning component:

$$W_{spec\,i} = \frac{m_i \eta Q_i}{t_{max}}. \quad (4)$$

In the conditions of these workings, the potential origins of significant fire are the following mining machines: Epiroc Boomer 282 drilling rig; Epiroc ST-1030 LHD; and the Sandvik TH 320 dump truck. A comparison of technical data shows that the Sandvik TH 320 dump truck is most hazardous when burning, since it has a maximum fire load. In this regard, the specific heat and gas releases should be calculated for this vehicle only.

The results of calculating the equivalent heat releases during combustion a Sandvik TH 320 dump truck are presented in Table 1.

According to the calculation results, the burning time of a Sandvik TH 320 dump truck will be 108.0 minutes. At the same time, the average heat generation will be 4.67 MW.

In order to calculate the specific gas releases, it is necessary to know the specific volume of a certain equipment component combustion products and the composition of the combustible mass.

According to the Fire Extinguishing Manager's Handbook [15], the specific volume of combustion products when burning diesel fuel, oil, rubber is: 11.95, 11.86, 10.79 m^3/kg, respectively. At the same time, the basic composition of the combustion products originating from the combustion of diesel fuel, oil, and rubber [16] is as follows:

– diesel fuel – 86.3 % C^G, 13.3 % H^G, 0.3 % S^G, 0.1 % ($O^G + N^G$);

– luboil – 86.5 % C^G, 12.6 % H^G, 0.4 % S^G, 0.5 % ($O^G + N^G$);

– rubber – 85.5 % C^G, 11.8 % H^G, 2.0 % S^G, 0.7 % ($O^G + N^G$).

Thus, carbon compounds are the key components of the combustion products of the involved materials. At the same time, a fire will largely release only carbon dioxide CO_2. Carbon monoxide CO, as a by-product of the combustion reaction, will be significantly released only in the conditions of oxygen shortage.

In order to simplify the solution of the emergency gas distribution problem, the oxygen content in the air arriving at a fire origin is assumed to be sufficient for the combustion reaction to occur normally. As a result the content of carbon monoxide CO in the combustion products is negligible. Then, as characteristic gas releases from a fire, we can take carbon

Table 1

Heat generation from dump truck burning

Dump Truck	Component	Weight, kg	Maximal heat generation, MW	Burnout time, min	Equivalent heat generation, MW
Sandvik TH 320	fuel	283.0	4.32	39.5	1.58
	luboil	340.2	4.54	44.3	1.87
	rubber	278.0	1.22	108.0	1.22
	a dump truck burning time and the fire heat release:			*108.0*	*4.67*

dioxide CO_2 releases, m³, determined by the following formula [16]:

$$V_{CO_2} = \left(0.0187 + \frac{C^G}{100}\right) V_G, \quad (5)$$

where C^G is carbon C content in a combustible material, %; V_G is total volume of combustion products, m³.

In this case, the specific gas releases, m³/min, of carbon dioxide CO_2 will be:

$$v_{CO_2} = \frac{V_{CO_2}}{t}, \quad (6)$$

where t is an equipment burning time, min.

According to the calculation results, the specific gas releases of carbon dioxide CO_2 during the combustion of a Sandvik TH 320 dump truck will be 72.2 m³/min.

Explosion development model parameterization

In mining conditions, the most probable explosions are those connected with:

– explosives (unauthorized firing);
– methane-air mixture (firedump);
– dust (coal or sulfide) [12].

The current study analyzes the unauthorized explosion of explosives and the explosion of a methane-air mixture. The study of explosions of coal and sulfide dust present in the mine workings of coal and pyrite mines, respectively, is outside the scope of our work. Thus, the paper focuses on the study of explosions in gas-hazardous mines with low dust hazard.

Assessing the consequences of an explosion and developing prevention measures and minimizing the damage area requires knowledge of the pressure distribution at the shock front at some distance from the origin of the explosion. At the same time, the calculation of shock wave parameters at a distance from the explosion origin begins by determining the pressure at the point of origin.

According to the *Gas-Dynamic Calculation Technique*[2] the pressure in the explosion zone, ΔP_f, MPa, depends on the dimensionless length of the active combustion area in accordance with the dependence shown in Fig. 4.

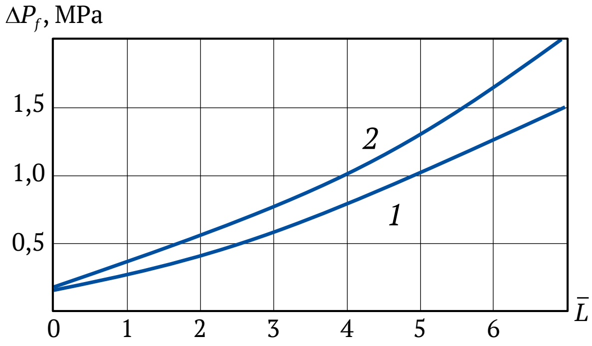

Fig. 4. Excess pressure in an explosion zone as a function of dimensionless length of a working:
1 – in the case of a methane explosion; *2* – in the case of a methane and coal dust explosion

The dimensionless length of an active combustion area is the length of a working length part from the nucleation site for ignition to the "combustible mixture-air" interface and can be deter-mined by the following formula[3]:

$$\bar{L} = \sum_{i=1}^{n} \frac{L_i P_i}{4 S_i}, \quad (7)$$

where L_i is the length of the i-th section of the explosion zone, m; $i = 1, 2, ..., n$ is the actual number of the sections; S_i is cross-sectional area of the i-th section of a working, m²; P_i is a working perimeter, m (in the case of an arched working $P = 3.84\sqrt{S}$).

When calculating an unauthorized explosion of explosives in a mine, the required parameter can be determined by the following formula [12]:

$$\bar{L} \approx \frac{M_{es} q_{es} P}{7 S^2}, \quad (8)$$

where M_{es} is mass of an explosive, kg; q_{es} is specific heat of an explosive, depending on its type, MJ/kg.

Thus, in order to determine the pressure in the origin of an unauthorized explosion of an explosive, it is sufficient to know its type and mass.

For example, under the conditions of these workings, AS-8 granulite weighing 180 kg is used to perform a drivage cycle in each mine working. Taking this into account, the dimensionless length of the active combustion area is 7.3 m.

It is more difficult to calculate the pressure in a methane-air mixture explosion origin. This is due to the fact that when calculating a predicted methane-air mixture explosion, the required dimensionless length of the active combustion area $\bar{L}$, actually determined by the volume of a working filled with an explosive mixture, can be determined only approximately.

[2] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia "On implementing the "Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions" dated April 27, 2004, 16 p.

[3] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia "On implementing the "Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions" dated April 27, 2004, 16 p.

One optimal approach to determining the maximum gas volume of a mine working, m^3, is to calculate the gas content of rocks in terms of free combustible gases and their minimum concentration sufficient to cause an explosion:

$$V_g = \frac{gS_{sink}(L_{sink} + B)100}{C_{low}}, \quad (9)$$

where g is gas content of rocks (free combustible gases), m^3/m^3; S_{sink} is drivage cross-sectional area of a working, m^2; L_{sink} is a blast cut length, m; B is the length of the rock mass releasing gases in front of the working (a zone of greatest fracturing), m; C_{low} is lower explosive limit of methane, %.

The lower explosive limit of methane under normal conditions is 5 %. However, under conditions of pressure other than normal, it should be recalculated using the following formula [17]:

$$C_{low} = \frac{5}{k}, \quad (10)$$

where k is the coefficient for converting bulk concentration of methane to molar one ($k = p/98070$, where p бis barometric pressure in a working, Pa).

In this case, the dimensionless length of the active combustion area is found by the following formula:

$$\bar{L} = \frac{V_g}{S_{expl}}, \quad (11)$$

where S_{expl} is cross-sectional area of a working in the clear, m^2.

This approach assumes that methane is released into the near-face working space from the broken rock volume, as well as from the section of the abutment pressure zone in front of the face, which is most susceptible to fracturing (Fig. 5). The gas releases from the walls, roof, and bottom of a mine working exposed before blasting are not taken into account. This is due to their insignificance with regard to degassing these areas in previous driving cycles.

The blast cut length is 2.3 m in the conditions of these workings. At the same time, according to the findings of the study [18], the zone of greatest fracturing extends to a depth of 5.3 m from the face. With a gas content of rocks in terms of free combustible gases of 0.15 m^3/m^3 and lower explosive limit of methane of 4.11 % (working No. 1) and 4.02 % (working No. 2), the required dimensionless length of the active combustion area will be 29.1 m and 29.7 m for workings No. 1 and No. 2, respectively.

Fire development simulation findings

The creation of a fire development model is preceded by the development of ventilation and heat-and-gas-dynamic models of mine workings. In AeroNetwork software, the development of a ventilation model begins with the construction of the ventilation network topology. Then, for all mine workings, aerodynamic parameters (cross-sectional areas, perimeters, lengths, roughness coefficients) are set. On this basis, the aerodynamic drag of the network elements is calculated. Subsequently, information regarding ventilation facilities and draught sources, characterizing their operation modes, is entered into the model.

The heat-and-gas-dynamic model is parameterized by activating/deactivating the accounting of different physical processes that affect heat and gas distribution in mine workings. Considering a fire in a dead-end working, the heat-and-gas-dynamic calculation should take into account the following:

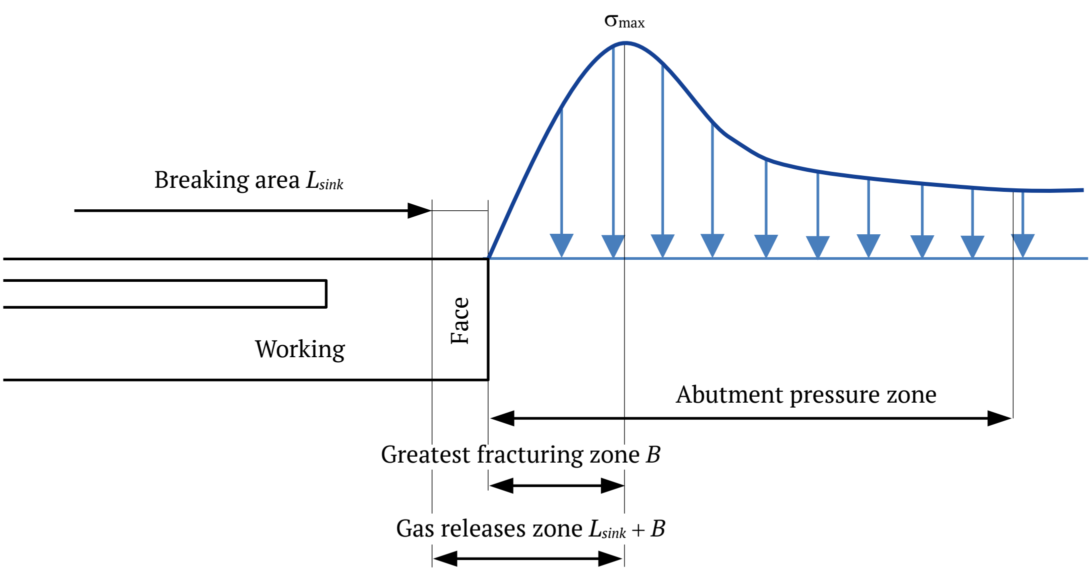

Fig. 5. Gas releases zone

air hydrostatic compression; pressure work; heat exchange in the "combustion origin – rock mass – air in a working – air in the duct" system; as well as the effect of thermal drop of ventilation pressure. A detailed description of the mathematical model of thermal and aerodynamic processes in AeroNetwork is presented in [19]. The assignment of a heat and gas release origin with the calculated parameters (4.67 MW, 72.2 m³/min) in the heat-and-gas-dynamic model allows the development of a fire to be calculated, in terms of determining gas and temperature distributions in the mine workings over time. At the same time, the simulation results directly depend on the location of a combustion origin.

In the case of these dead-end workings, the total break is hauled by LHDs running between the faces and the mine shaft. Therefore, a fire is possible in any part of the dead-end workings. However, given a concentration of mining works in the face space, a fire at the face should be considered

Given this particular problem, in the case of fire, the integrity of a duct is assumed not to have been violated due to its rigid metal construction and the location of the fire origin at the face. However, when a fire is located along the length of a dead-end working and a flexible non-fire-resistant duct is used, a possible violation of its tightness or breakage as a result of thermal exposure should be assumed.

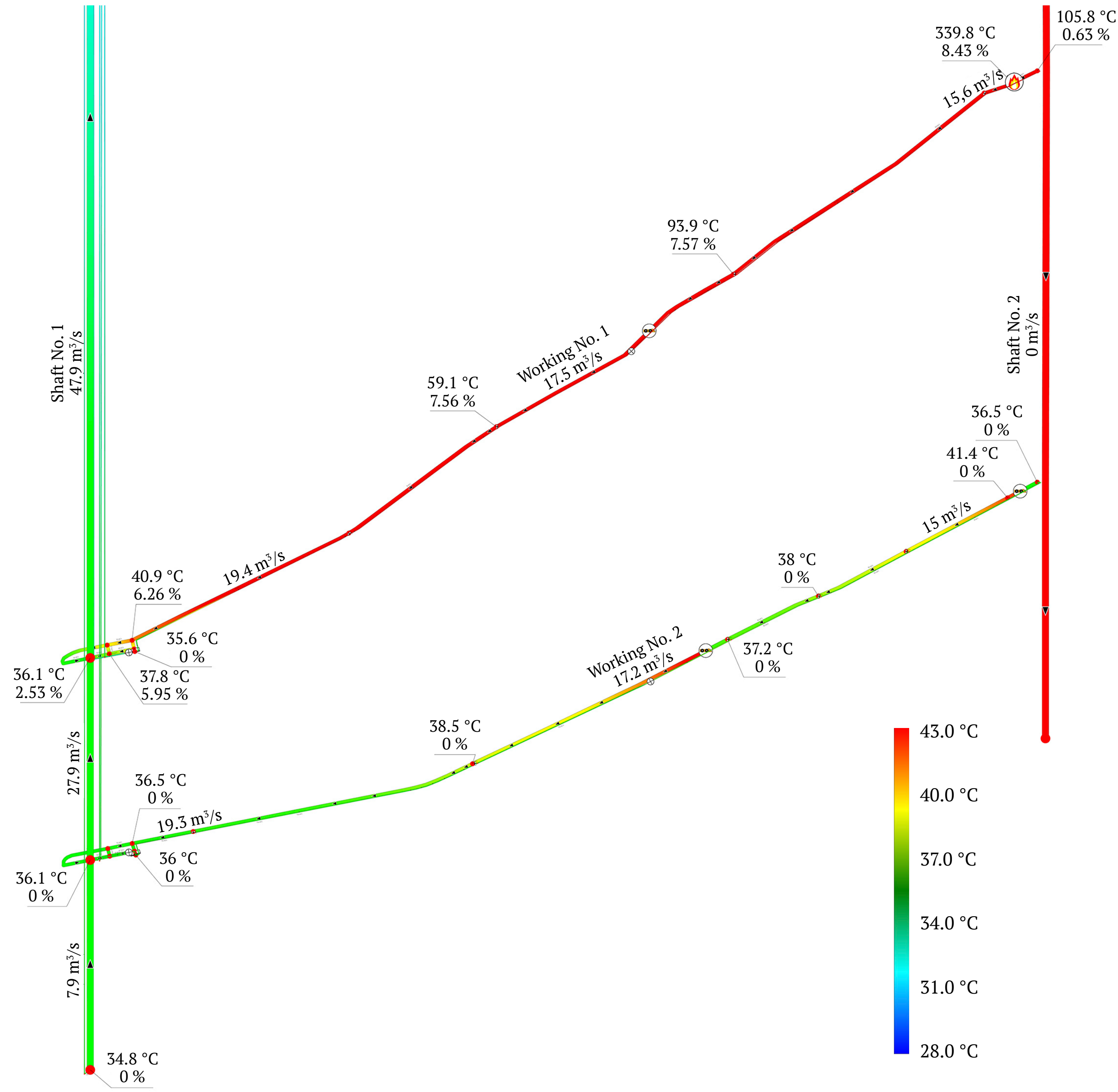

Fig. 6. Air temperature distribution in the mine workings in the event of a fire at the face of working No. 1

The results of the air temperature distribution simulation, 108 minutes after a fire break-out in working No. 1 are presented in Fig. 6. Additionally, the Figure shows the values of carbon dioxide CO_2 concentrations at key points in the working.

The simulation showed that a fire at the mouth of mine working No. 1 will not lead to a significant change in air flow-rate in working No. 2. At the same time, in the fire origin, the air temperature will reach 339.8° C, and the concentration of carbon dioxide CO_2 will achieve 8.43 %. It should be noted that a fire at the mouth of working No. 1 will not lead to hazardous air condi-tions in terms of pollution and heating in working No. 2. This is due to the fact that the heated combustion products, with a lower density compared to the air in the shaft, will be removed to-

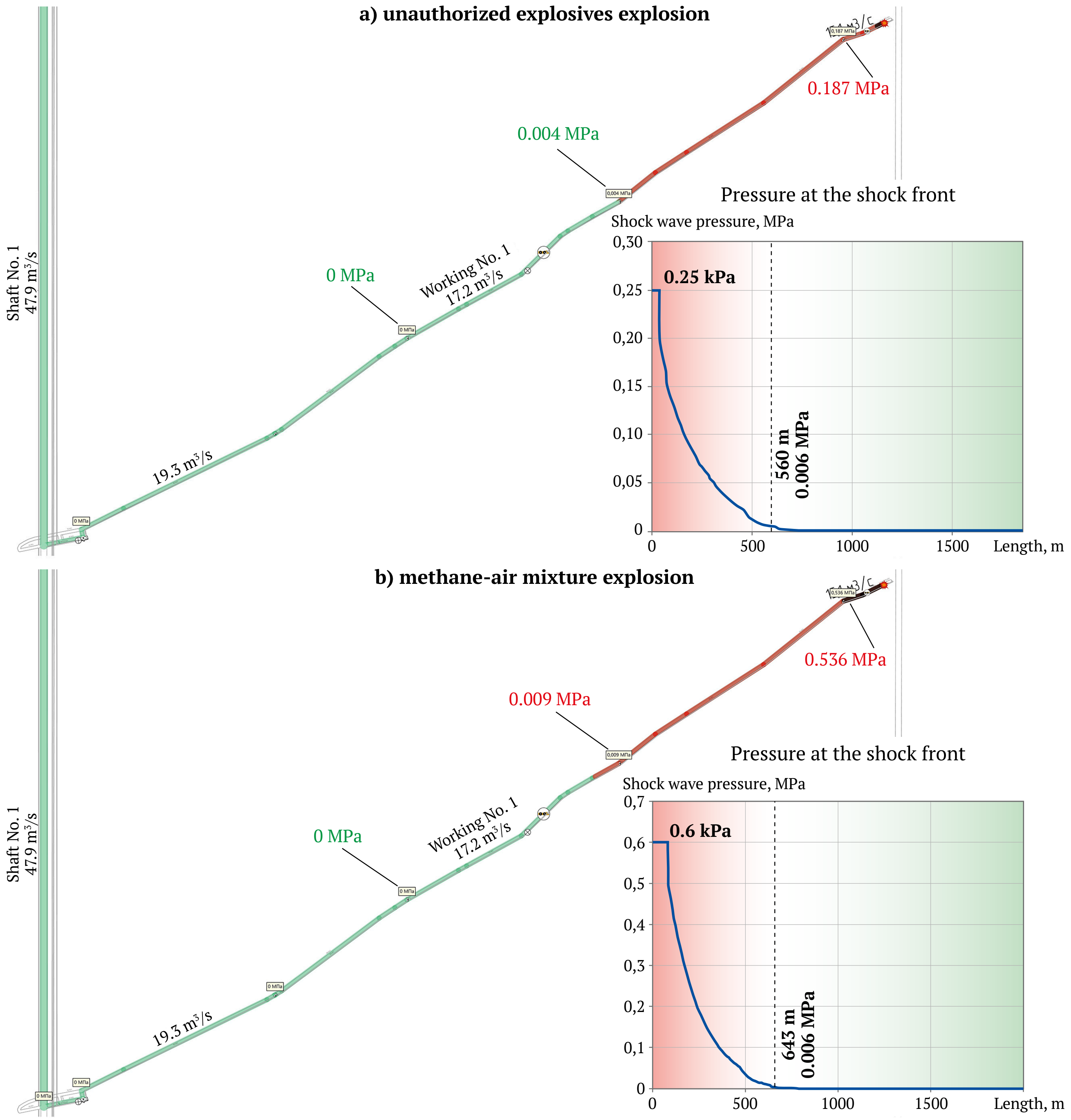

Fig. 7. Pressure distribution at the shock front at an explosion at the face of working No. 1:
a – explosive explosion; *b* – methane-air mixture explosion

wards daylight surface. In addition, the operation of surface fans supplying air and displacing smoke from working No. 1 to the outside will prevent origination of gas hazard conditions in mine working No. 2.

Similar results were obtained when simulating the development of a fire at the mouth of working No. 2. This was due to the identical ventilation parameters of these workings. However, in the event of a fire at the mouth of working No. 2, the combustion products will enter the shaft station at working No. 1, as a result of diffusion processes and thermal drop of ventilation pres-sure.

Results of shock wave propagation simulation

A model of shock wave propagation, equivalent to a fire development model, is based on the model of mine workings ventilation. Setting an explosion origin in the model with initial parameters (the type and mass of an explosive or the dimensionless length of the active methane-air mix-ture combustion area) allows the distribution of excess pressures in the workings at the time of the explosion to be calculated. However, the simulation results will depend on the location of the explosion origin.

An unauthorized explosion of explosives is possible in any part of a dead-end mine working, since the explosives are delivered from the mine shaft to the face. In turn, an explosion of a methane-air mixture is most likely at the face of a working. This is because the face is prone to bleed-ing and sudden gas release. We considered the consequences of explosive and methane-air mix-ture explosions at the face of a dead-end working and performed a comparative analysis.

The pressure distribution at the shock front at an explosion of explosives / methane-air mixture at the face of working No. 1 is shown in Fig. 7. In accordance with the *Gas-Dynamic Calcu-lation Methodology*[4], an excess pressure at the shock front equal to 0.006 MPa was taken as a shock wave hazard criterion for people in a mine.

The simulation showed that an explosion of explosives at the face of mine working No. 1 will cause excess pressure in the explosion origin of 0.25 MPa. At the same time, the zone of haz-ardous impact of the shock wave will spread over a distance of 560 m, corresponding to 30 % of the total length of the dead-end working (1840 m). When a methane-air mixture explodes at the face of mine working No. 1, the excess pressure in the explosion origin will be 0.6 MPa. The zone of hazardous shock wave will spread over a distance of 643 m, corresponding to 35 % of the total length of the dead-end working. Similar simulation results were obtained when considering the explosion at the mouth of working No. 2, the only difference being that in this case the zone of hazardous shock wave will have a larger propagation radius due to the rectilinearity of working No. 2. Thus, the explosion of methane-air mixture is of the greatest hazard in the conditions of the involved workings.

Conclusion

This study formulates a general principle for determining the parameters of mine fire and explosion models. The aim was to assess their development using the AeroNetwork analytical package. According to this principle, a fire development model parameterization consists in determining heat and gas releases from a combustion origin, taking into account the following fea-tures:

– to predict the potential most unfavorable conditions of a mine air in the event of an exogenous mine fire, a fire of equipment (a vehicle) only with a maximum fire load is advisable to be considered;

– the main fire load of a vehicle is fuel, oil, and rubber. In this way the fire load can be approximately determined based on the technical characteristics of a vehicle, such as the volume of the fuel tank, the volume of the hydraulic system, and the tire size;

– as heat and gas releases from a burning vehicle, the equivalent values determined by the recalculation for individual combustible components is advisable to be taken;

– taking into account the chemical composition of the fire load, it is sufficient to consider the propagation of carbon dioxide CO_2, in order to assess the toxicity of a mine air if a fire breaks out.

Parameterization of the explosion development model consists in determining the excess pressure at the shock front in an explosion origin. This takes the following features into account:

– excess pressure at the shock front in an explosion origin, determined depending on the dimensionless length of the active combustion area $\bar{L}$;

– in the event of an unauthorized explosive explosion, the parameter $\bar{L}$ is determined by the weight and specific heat of an explosive, as well as the geometric parameters of a mine working;

– in the event of a methane-air mixture explosion, the parameter $\bar{L}$ takes the following into account: the gas content of rocks in terms of free combustible gases; the length of a blast cut; the size of the area of increased fracturing; and the lower explosive limit of methane, calculated on the basis of the actual pressure in a working.

[4] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia "On implementing the "Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions" dated April 27, 2004, 16 p.

References

1. Pakhomov V.P., Rudakova L.V. Catastrophes formed by a technical reaction of the character of mining industries. *Economy of Regions*. 2006;(2):23–36. (In Russ.)

2. Remizov A.V., Hobta A.A. The causes of emergency situations in coal mines and the possibilities of their prevention. *Bulletin of the Siberian State Industrial University*. 2016;(1):14–16 (In Russ.) URL: https://www.sibsiu.ru/downloads/public/vestniksibgiu/vestnik15.pdf

3. Brake D.J. Fire modelling in underground mines using Ventsim Visual VentFIRE Software. In: Chalmers D. (ed.) *The Australian Mine Ventilation Conference*. Adelaide, South Australia, 1–3 July 2013. The AusIMM; 2013. Pp. 265–276. URL: https://ventsim.com/wp-content/uploads/2019/04/Fire_Modelling_in_Underground_Mines_using_Ventsim_VentFIRE.pdf

4. De Rosa M.I. *Analysis of mine fires for all US metal/non-metal mining categories, 1990–2001*. National Institute for Occupational Safety and Health (NIOSH); 2004. URL: https://www.cdc.gov/NIOSH/Mining/UserFiles/works/pdfs/2005-105.pdf

5. Paleyev D., Lukashov O. Software complex "Mining Aerology (Ventilation)". *Russian Mining Industry*. 2007;(6):20–23. (In Russ.) URL: https://mining-media.ru/ru/article/newtech/866-programma-rascheta-ventilyatsionnykh-rezhimov-v-shakhtakh-i-rudnikakh

6. Lönnermark A., Blomqvist P. *Emissions from tyre fires*. Borås, Sweden: SP Swedish National Testing and Research Institute; 2005.

7. Liskova M.Yu., Naumov I.S. Design of emergency situations in mines. *Nauchnyye Issledovaniya i Innovatsii*. 2013;7(1–4):78–81. (In Russ.)

8. Shalimov A.V. Numerical modeling of air flows in mines under emergency state ventilation. *Journal of Mining Science*. 2011;47(6):807–813. https://doi.org/10.1134/S106273914706013X (Orig. ver.: Shalimov A.V. Numerical modeling of air flows in mines under emergency state ventilation. *Fiziko-Texhnicheskiye Problemy Razrabbotki Poleznykh Iskopaemykh*. 2011;(6):84–92. (In Russ.))

9. Hansen R., Ingason H. *Full-scale fire experiments with mining vehicles in an underground mine*. Research report. Västerås, Sweden: Mälardalen University; 2013.

10. Hansen R. Analysis of methodologies for calculating the heat release rates of mining vehicle fires in underground mines. *Fire Safety Journal*. 2015;71:194–216. https://doi.org/10.1016/j.firesaf.2014.11.008

11. Danilov A.I., Maslak V.A., Vagin A.V., Sivakov I.A. Numerical simulation of a subway car fire. *Fire and Explosion Safety*. 2017;26(10):27-35. (In Russ.) https://doi.org/10.18322/pvb.2017.26.10.27-35

12. Paleev D.Yu., Lukashov O.Yu., Kosterenko V.N. et al. Shock waves during explosions in coal mines. In: *Mining Engineer's Library. Volume 6 "Industrial Safety". Part 3.* Moscow: Gornoe Delo Publ, Cimmerian Center LLC; 2011. 312 p. (In Russ.)

13. Smolin I.M., Poletayev N.L., Gordienko D.M. et al. *Manual for the application of SP 12.13130.2009 "Determining the categories of premises, buildings, and outdoor installations in terms of explosion and fire hazard"*. Moscow: VNIIPO Publ.; 2014. 147 p. (In Russ.) URL: https://ohranatruda.ru/upload/iblock/c84/4293768102.pdf

14. Karsakov O.G. On the problem of justifying the critical time of a fire at the initial stage. *Problemy obespecheniya bezopasnosti pri likvidatsii posledstviy chrezvychaynykh situatsiy*. 2015;4(1–1):330–332. (In Russ.)

15. Ivannikov V.P., Klyus P.P. *Fire extinguishing manager's handbook*. Moscow: Stroyizdat Publ.; 1987. 288 p. (In Russ.)

16. Bystritsky G.F., Gasangadzhiev G.G., Kozhichenkov V.S. *General power engineering. Core equipment*. Textbook. 2nd update. Moscow: Yurait Publ. House; 2018. 416 p. (In Russ.) URL: https://mx3.urait.ru/uploads/pdf_review/90FAE97C-FD7D-41FC-ACD5-6E038A39261C.pdf

17. Kolesnitchenko I.E., Kolesnitchenko E.A., Artemiev V.B., Icheretchukin V.G. Dependence of volumetrically concentration limit of methane blasting on physical parameters of the atmosphere. *Mining Informational and Analytical Bulletin*. 2015;(S7):174–181. (In Russ.)

18. Cherdancev N.V., Zykov V.S. The solution to a problem of in-seam working areas abutment pressure parameters determination based on the simulation experiment. *Bulletin of Scientific Centre VostNII for Industrial and Environmental Safety*. 2017;(3):16–30. (In Russ.) URL: http://vestnik.nc-vostnii.ru/arhiv/vypusk-3-2017/reshenie-zadachi-opredeleniya-parametrov-opornogo-davleniya-v-okrestnosti-plastovoy-vyrabotki-na-osnove-vychislitelnogo-eksperimenta/

19. Levin L. Y., Semin M. A., Zaitsev A. V. Mathematical methods of forecasting microclimate conditions in an arbitrary layout network of underground excavations. *Journal of Mining Science*. 2014;50(2):371–378. https://doi.org/10.1134/S1062739114020203 (Orig. ver.: Levin L. Y., Semin M. A., Zaitsev A. V. Mathematical methods of forecasting microclimate conditions in an arbitrary layout network of underground excavations. *Fiziko-Texhnicheskiye Problemy Razrabbotki Poleznykh Iskopaemykh*. 2014;(2):154–161. (In Russ.))

Information about the authors

Maxim O. Perestoronin – Postgraduate Student, Mining Thermal Physics Sector, Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0009-0003-0203-9304, Scopus ID 57701516700; e-mail per.maks1m.97@gmail.com

Oleg S. Parshakov – Cand. Sci. (Eng.), Mining Thermal Physics Sector, Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0000-0001-5545-442X; Scopus ID 57202379375; e-mail olegparshakov@gmail.com

Maxim D. Popov – Postgraduate Student, Mining Thermal Physics Sector, Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0009-0007-6388-608X, Scopus ID 57208722129; e-mail maxpan09@gmail.com

Поступила в редакцию	06.10.2022	**Received**	06.10.2022
Поступила после рецензирования	19.01.2023	**Revised**	19.01.2023
Принята к публикации	27.01.2023	**Accepted**	27.01.2023