Arch. Min. Sci. **70** (2025), 3, 403-421

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI: https://doi.org/10.24425/ams.2025.156292

PAVEL ZAPLETAL[1], JAROSLAVA KOUDELKOVÁ[1*], VÍTĚZSLAV URBANEC[2], MARTIN ŠTEMBERKA[2], GRZEGORZ PACH[3], ZENON RÓŻAŃSKI[3], ADAM NIEWIADOMSKI[3]

THE REQUIRED AMOUNT OF MINE AIR PASSING THROUGH THE EMERGENCY PASSAGE INTO THE MINE

In mines, providing proper ventilation during emergencies is a key aspect of ensuring safety and protecting human lives. In the case of indirect intervention by taking extreme measures (the closure of the entire mine using fire covers), it is necessary to ensure an emergency passage of miners to the surface providing a sufficient amount of mine air for them. The speed of the air must not exceed the limit for the safe passage of people, and must not cause unstable fan operation. The modelling of this problem in this case is carried out on a simplified ventilation network, in which two interconnected pits at a depth of 1000 m are displayed. The input data and limit values correspond to the valid legislation of the Czech Republic, but the resulting proposed methodology is universal and applicable to any mine or underground space that is artificially ventilated, and the parameters of the ventilation network are known. The issue of safety is always the main and key element of underground mining or underground work, and this article provides a model example of how to approach it even in the most difficult situations.

Keywords: Velocity; emergency; operating point; mine fire; mine air; volume flow

1. Introduction

In the planning of mining activities, ensuring the safe operation of the entire mine and all related processes must always be the primary concern. Nevertheless, certain events remain beyond human control, as nature may respond to anthropogenic disturbances in unpredictable ways. Among the most common manifestations of such geodynamic imbalance caused by mining

[1] VŠB-TECHNICAL UNIVERSITY OF OSTRAVA, FACULTY OF MINING AND GEOLOGY, CZECH REPUBLIC
[2] CZECH MINING AUTHORITY PRAGUE, CZECH REPUBLIC
[3] SILESIAN UNIVERSITY OF TECHNOLOGY, 2A AKADEMICKA STR., 44-100 GLIWICE, POLAND

* Corresponding author: jaroslava.koudelkova@vsb.cz

operations are seismic events (mining tremors) [15], sudden outbursts of rock and gas [13,14,32], gas and coal dust explosions [16,17,24], and – last but not least – fires, whether of endogenous origin [2,18,21] or triggered by external factors [20,22].

A mine fire is defined as an incident of uncontrolled combustion occurring within underground mine workings. Such fires may be initiated by various factors, including the ignition of methane [1], coal dust, or other flammable substances. Additional ignition sources may include technical failures such as electrical short circuits. Mine fires represent a severe hazard [12], as they lead to the release of toxic gases and can compromise the structural integrity of entries, workings, and tunnels. As a result, comprehensive safety measures must be implemented, including flame detection systems [23], fire suppression equipment [25], and clearly defined evacuation protocols for underground personnel [26,27].

Firefighting in an underground mine is an inherently complex and hazardous operation [28,29], requiring the coordination of multiple response measures and posing significant risks to firefighting personnel and mine rescue teams [30]. The initial and fundamental step in combating a mine fire is the isolation of the affected zone by sealing off the underground fire area to prevent the propagation of flames and smoke into adjacent workings. Once the fire zone is effectively enclosed, active extinguishing efforts commence, typically involving the use of fire extinguishers and water hoses delivered to the fire site through designated access points and mine tunnels.

If the fire is too extensive or poses excessive risk to permit active firefighting, passive suppression methods may be employed. These involve the hermetic sealing of the underground fire zone to eliminate the inflow of oxygen, thereby extinguishing the fire through oxygen deprivation. Although passive methods significantly reduce the risk to personnel, the extinguishment process may take several days – or even weeks – before the fire is fully suppressed [31].

This article presents a methodology for managing ventilation network interventions in situations where it becomes necessary to seal the entire mine, maintaining only a limited intake route to supply air for active firefighting operations. With respect to the objectives of this study, the mine ventilation network and the associated numerical model were deliberately simplified. The article presents a basic method of airflow regulation without incorporating complex input parameters such as temperature, humidity, or natural ventilation pressure. This approach allows for a clear and comprehensible analysis of the mechanical effects of resistance changes on the stable operation of the main ventilation fan, which is crucial for ensuring safe conditions during firefighting and personnel evacuation. The available literature offers little guidance on this specific scenario, with only a few outdated and non-English-language sources addressing the issue [12,34,38,39], most of which are not readily accessible online. This problem was primarily explored during the peak era of coal mining, and such critical events are relatively rare in modern practice. Nevertheless, the topic remains highly relevant due to its strong connection with compliance to mine safety regulations – a subject that forms the core of our research focus.

2. Definition of the issue

If direct firefighting efforts prove ineffective, indirect suppression methods must be employed. The fundamental principle of this approach is the airtight sealing of the underground fire zone to prevent the ingress of oxygen, thereby eliminating the conditions necessary for combustion.

In the case of large-scale fires that cannot be controlled or confined to a limited area, indirect fire suppression is implemented through the drastic measure of sealing the entire mine.

This is achieved by installing fire-resistant covers on the downcast shafts and employing suction devices attached to the inlets of the main mine fan.

Mathematical modelling of mine ventilation under such extreme conditions [2-4,10] is highly complex and technically demanding. In this study, we focus on a specific aspect arising from the requirements of Czech mining legislation [36] – namely, the obligation to ensure the existence of an emergency passage from the sealed downcast airways to the surface and to determine the necessary volumetric airflow through this passage. In the event of downcast shaft closure, the emergency passage is intended to function both as an alternative ventilation route for mine air supply and as an access and evacuation pathway for personnel.

The emergency passage is connected to the surface and discharges directly into the shaft. Under standard operating conditions, the passage remains sealed, and zero airflow is assumed within it. Its junction with the shaft is located approximately 10 meters below the surface and is accessible via the shaft's manway compartment.

Several theoretical considerations influence the determination of the required volumetric airflow through the emergency passage under such extreme conditions. These simultaneously define the core of the problem addressed in this study:

- Following the closure of the fire-resistant cover on the downcast shaft, virtually all intake air must be routed through the emergency passage into the mine.
- The emergency passage has a significantly smaller cross-sectional area compared to the main shaft.
- The closure of the downcast shaft increases the overall aerodynamic resistance of the mine, thereby reducing the volumetric airflow.
- To ensure safe evacuation through the emergency passage, airflow velocity must be limited to allow personnel movement, which may necessitate a further reduction in airflow through the passage – and by extension, through the entire mine.
- The resulting increase in aerodynamic resistance shifts the operating point of the main fan closer to its stability limit.
- Under these conditions, compliance with regulations governing minimum mine air quantities can only be ensured by adjusting airflow on the suction side of the main fan (i.e., by unsealing the upcast shaft building).
- This regulatory approach addresses both critical issues: it decreases the airflow through the emergency passage while simultaneously increasing the total volumetric flow through the fan, thus stabilizing the fan's operation by moving its operating point away from the instability threshold.

Based on the above considerations, the problem of determining the required airflow through the emergency passage can be formulated as follows: it is necessary to establish the amount of air that will ensure (i) safe personnel movement within the passage, (ii) stable operation of the main mine fan, and (iii) acceptable overall ventilation conditions within the mine.

A schematic representation of this problem and its resolution is provided in Fig. 1, which illustrates the following scenarios:

(A) Stable operation of the mine fan (MF) with minimal suction from the surface via the upcast shaft building.

(B) Closure of fire-resistant covers on the downcast shaft while maintaining the emergency passage open – resulting in increased aerodynamic resistance and the potential for unstable fan operation.

(C) Unsealing of the upcast shaft building – enhancing surface suction, thereby reducing aerodynamic resistance and restoring stable operation of the main ventilation fan (MF).

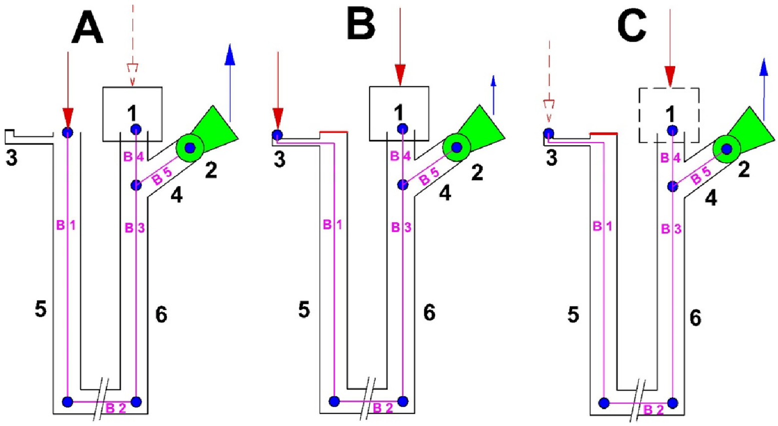

Fig. 1. Schematic representation of the principle for determining the required airflow through the emergency passage. Legend: (1 – upcast shaft building, 2 – main mine fan, 3 – emergency passage from the mine, 4 – ventilation air duct, 5 – downcast shaft, 6 – upcast shaft, B1-B5 – branches)

Fire-resistant hatches fall under the scope of fire protection measures for main mine workings, as defined in §§175, 178, and 179 of Decree No.22/1989 Coll. of the Czech Mining Authority on Occupational Safety, Health Protection, and Operational Safety during Mining Activities and the Extraction of Unworked Mineral Deposits Underground. Based on the cited provisions of the safety regulations, specific obligations related to the design of the mine ventilation network can be inferred, including:

- Determining the required volumetric airflow through the emergency passage.

Within the mine ventilation network, the emergency passage is considered a part of the intake shaft. Under normal operating conditions, zero volumetric airflow is assumed through this passage. In contrast, under emergency conditions, zero airflow is assumed through the downcast shaft, meaning that all mine air flows exclusively through the emergency passage. In terms of the ventilation network, this situation corresponds solely to a change in aerodynamic resistance in the respective branch, depending on whether the airflow passes through the shaft or the emergency passage.

3. Of Practical methods for determining the minimum volumetric airflow through the emergency passage

The ventilation documentation prepared for individual sites of the mining company OKD [40] demonstrates varying approaches to resolving the issue of determining the minimum volumetric airflow through the emergency passage.

At the decommissioned Darkov Mine, the minimum airflow was determined using mathematical network modelling. In this model, the resistance of the downcast shafts in the branches near the upcast shaft building was replaced by the aerodynamic resistance of the emergency passage. Subsequently, the intake resistance was reduced to its minimum in order to minimize the overall airflow while maintaining the main fan's operating point within its stable performance range. The resulting specified minimum volumetric airflow through the emergency passage, under these conditions, was considered the target value up to this point, the methodology appears sound. However, the resulting airflow was not evaluated with respect to the resulting air velocity in the emergency passage. The predicted velocity would, in fact, exceed acceptable levels for safe pedestrian movement – see TABLE 1.

At the ČSM Mine, the documentation states the minimum airflow through the emergency passage without any description of the method used. It can only be inferred that the value was derived from the performance curve of the main fan operating near its minimum capacity at the stability threshold. As with the Darkov Mine, this approach also neglects to evaluate the resulting air velocity in the passage, rendering the value practically unusable for ensuring safe evacuation conditions.

TABLE 1

Overview of Specified Minimum Airflows Through Emergency Passages

Mines (names)	**Minimum cross-section of the emergency passage**	**Specified minimum volumetric airflow**	**Air velocity at minimum cross-section**	**Maximum allowable air velocity for safe personnel movement**
	[m^2]	**[$m^3 \cdot s^{-1}$]**	**[$m \cdot s^{-1}$]**	**[$m \cdot s^{-1}$]**
ČSM South 3	3.0	116.7	38.90	10.00
ČSM North 1	2.0	100.0	50.00	10.00
Darkov – ČSA 2	4.4	133.3	30.30	10.00
Darkov – Jan	5.4	135.1	25.00	10.00

Although the available overview of current practices for determining the specified minimum volumetric airflow through emergency passages in downcast shafts is not exhaustive, it clearly indicates that the applied methods and resulting values are, to a significant extent, influenced by an effort to formally comply with regulatory requirements rather than to derive a technically sound solution. In the event of an actual emergency, these results cannot be responsibly recommended as a reliable basis for decision-making.

This analysis indicates that, while the safety regulations impose a requirement to determine the specified minimum volumetric airflow through the emergency passage, they do not prescribe any standardized methodology for doing so. The absence of a uniform procedural framework negatively affects the practical implementation of this requirement in operational settings.

4. Proposal for determining the specified minimum volumetric airflow through the emergency passage

The purpose of assessing the impact of fire-resistant covers installed on downcast shafts in the context of mine ventilation is to determine a volumetric airflow that, in the event of an emergency, will ensure continuous ventilation through the emergency passage and permit safe personnel movement.

Given the absence of relevant sources addressing this issue, we present our own methodological proposal, which was practically verified at the ČSA Mine and remains partially in use at this site.

The installation of fire covers on downcast shafts increases the aerodynamic resistance of the mine, resulting in a reduction in the volumetric airflow and shifting the operating point of the main ventilation fan closer to the zone of unstable operation.

Two limiting conditions must be respected when determining the specified minimum volumetric airflow through the emergency passage:

- The air velocity within the emergency passage must not exceed the maximum allowable velocity for safe personnel movement.
- The resulting aerodynamic resistance of the mine, after closure of the fire covers, must not induce unstable operation of the ventilation fan.

The maximum permissible air velocity is regulated by Decree No. 22/1989 Coll. [36], Section 85, Paragraph 2, which states:

"*The velocity of mine air shall not exceed:*

a) 4 m/s in opening and preparatory mine workings, tunnels, and chambers,

b) 10 m/s in other workings with personnel movement or regular transport,

c) 15 m/s in other workings without personnel movement or regular transport."

(*Unofficial translation of Decree No. 22/1989 Coll., Section 85, Paragraph 2*)

During an emergency, the emergency passage falls under the category of "other mine workings with personnel movement," and the air velocity within it must therefore be limited to $10\ \mathrm{m \cdot s^{-1}}$.

Based on this condition, the maximum volumetric airflow $Q_{p\max}$ passing through the emergency passage can be expressed as:

$$Q_{p\max} = v_{\max p} \cdot S_s = 10 \cdot S_s\ [\mathrm{m^3 \cdot s^{-1}}] \quad (1)$$

Where:

S_s – cross-sectional area of the emergency passage $[\mathrm{m^2}]$,

$v_{\max p}$ – maximum permissible air velocity in the emergency passage $[\mathrm{m \cdot s^{-1}}]$,

$Q_{p\max}$ – maximum volumetric airflow passing through the emergency passage $[\mathrm{m^3 \cdot s^{-1}}]$.

The unstable operation of the main ventilation fan is defined by the **critical aerodynamic resistance** of the mine. In the event of an emergency requiring the closure of the downcast shaft using a fire-resistant cover, while simultaneously maintaining proper ventilation, it must be verified that the resulting increase in mine resistance does not exceed this critical threshold.

If the mine resistance does exceed the critical value, it is necessary to take advantage of the fact that the mine resistance from the main ventilation fan duct to the collar of the downcast shaft (branches B1, B2, and B3) is arranged in parallel – within the ventilation network – with the suction path through the upcast shaft building (branch B4). By reducing the aerodynamic resistance of the suction side, the increase in total mine resistance resulting from the closure of the fire cover can be compensated.

Reducing the suction resistance increases the volumetric airflow through the fan; however, it simultaneously decreases the volumetric airflow through the mine itself [33]. Therefore, when implementing such a regulation measure, care must be taken to ensure that the **specified minimum volumetric airflow** through the mine is still maintained during the emergency.

The described changes in airflow distribution are implemented in the mine ventilation network model [5-7] during the process of calculating the required volumetric airflow through the emergency passage.

If the resulting volumetric airflow does not exceed the **maximum permissible volumetric airflow** through the emergency passage as defined by Eq. (1), a feasible solution has been found. If the result exceeds this limit, further adjustment of the suction resistance is required.

5. Model example

As a reference scenario, we use a simplified model of mine ventilation network, specifically applying an incompressible flow calculation that neglects temperature and humidity effects. The mathematical model represents a fictional mine [10] and includes the following elements: a 1000 m deep downcast shaft, a 900 m deep upcast shaft (in accordance with the design principle that the bottom of the upcast shaft must be positioned higher than the bottom of the downcast shaft), the airflow duct of the mine fan, the suction side of the main fan, and a single horizontal branch connecting the two shafts, representing the working level.

The ventilation network calculation is performed under the assumption of a constant air density of $\rho = 1.2\ \text{kg}\cdot\text{m}^{-3}$, which implies uniform air temperature and pressure throughout the system. This simplified modelling approach is adopted to clearly demonstrate trends in pressure distribution within the mine, variations in volumetric airflow due to the closure of fire-resistant covers, and the resulting influence on the stable operation of the main ventilation fan.

Aerodynamic resistances required for the ventilation network calculations [9] are taken from the standardization guidelines for mine ventilation developed in the Ostrava-Karviná coal district [35].

A detailed description of the individual branches of the ventilation network, along with the input parameters used in the model, is provided in TABLE 2.

TABLE 2

Description and parameters of the branches in the mine ventilation network model

Branch no.	Start node	Start depth [m]	End node	End depth [m]	Aerodynamic Resistance [$\text{Pa}\cdot\text{s}^2\cdot\text{m}^{-6}$]	Mine work	Length [m]
0	6	0	1	0	0.00000	Surface	—
1	1	0	2	1000	0.02460	Downcast shaft	1000
2	2	1000	3	900	0.35000	Working Level	3000
3	3	900	4	0	0.02619	Upcast shaft	900
4	6	0	4	0	30.0000	Surface air intake through the upcast shaft building	20
5	4	0	5	0	0.03000	Ventilation air duct	50
6	5	0	6	0	0.00000	Main mine fan	5

The configuration of individual branches and nodes in the mine ventilation network model, along with the resulting distribution of volumetric airflows and pressures obtained from the incompressible flow calculation, is illustrated in the ventilation diagram in Fig. 2.

This calculation serves as the reference baseline for the majority of comparisons presented in this study. The corresponding numerical output, generated using VENTGRAPH software, is provided in TABLE 3.

Note: The presented values ($p_{inlet/outlet}$) correspond to the aerodynamic potential at the nodes of the ventilation network, as determined by the algorithm of the SÍŤ software. These are not actual absolute pressures in the physical sense.

TABLE 3

Output of the incompressible flow calculation for the default state of the mine ventilation network model

B	NP1	NP2	h1 [m]	h2 [m]	R [$Pa \cdot s^2 \cdot m^{-6}$]	Q [$m^3 \cdot s^{-1}$]	ρ [$kg \cdot m^{-3}$]	Q_m [$kg \cdot s^{-1}$]	ΔP_b [Pa]	P [W]	p_{inlet} [Pa]	p_{outlet} [Pa]
0	6	1	0.0	0.0	0.000000	83.64	1.200	100.37	0.0	0	0.0	0.0
1	1	2	0.0	1000.0	0.024600	83.64	1.200	100.37	172.1	14939.1	0.0	–172.1
2	2	3	1000.0	900.0	0.350000	83.64	1.200	100.37	2448.4	204780.3	–172.1	–2620.5
3	3	4	900.0	0.0	0.261900	83.64	1.200	100.37	183.2	15323.4	–2620.5	–2803.7
4	6	4	0.0	0.0	30.000000	9.36	1.200	11.23	2803.7	26243.4	0.0	–2803.7
5	4	5	0.0	0.0	0.030000	93.00	1.200	111.60	259.5	24129.8	–2803.7	–3063.2
6	5	6	0.0	0.0	0.000000	93.00	1.200	111.60	0.0	0.0	–3063.2	0.0

The corresponding coefficient values used in the model for the fan characteristic at air density $\rho = 1.2\ kg \cdot m^{-3}$ are listed in TABLE 3a. The fan is located in **branch 6**, and its pressure–flow relationship is described by a second-degree polynomial of the form:

$$\Delta p_{fan} = A0 + A1 \cdot Q + A2 \cdot Q2 + A3 \cdot Q3$$

TABLE 3a

Polynomial coefficients and operating parameters of the main fan (branch 6)

Branch	$A0$	$A1$	$A2$	$A3$	Q [$m^3 \cdot s^{-1}$]	Δp_{fan} [Pa]	*Puseful* [kW]
6	1840.1	36.029	–0.246	0.00	93	3063.2	284.9

Explanation of parameters used in TABLES 3, 3a, 5, 5a, 6, and 6a:

B – branch number,
NP_1 – input node number,
NP_2 – output node number,
h_1 – depth of the input node [m],
h_2 – depth of the output node [m],
R – aerodynamic resistance of the branch [$Pa \cdot s^2 \cdot m^{-6}$],
Q – the volumetric flow of air in the branch [$m^3 \cdot s^{-1}$],
ρ – air density in the branch [$kg \cdot m^{-3}$],
Q_m – air mass flow in the branch [$kg \cdot s^{-1}$],

ΔP_b – pressure drop on the branch [Pa],
ΔP_{fan} – pressure drop on the main fan [Pa],
P – power loss in the branch [W or kW],
P_{useful} – useful power output of the fan [kW],
p_{inlet} – aerodynamic potentials at the network inlet nodes [Pa],
p_{outlet} – aerodynamic potentials at the network outlet nodes [Pa].

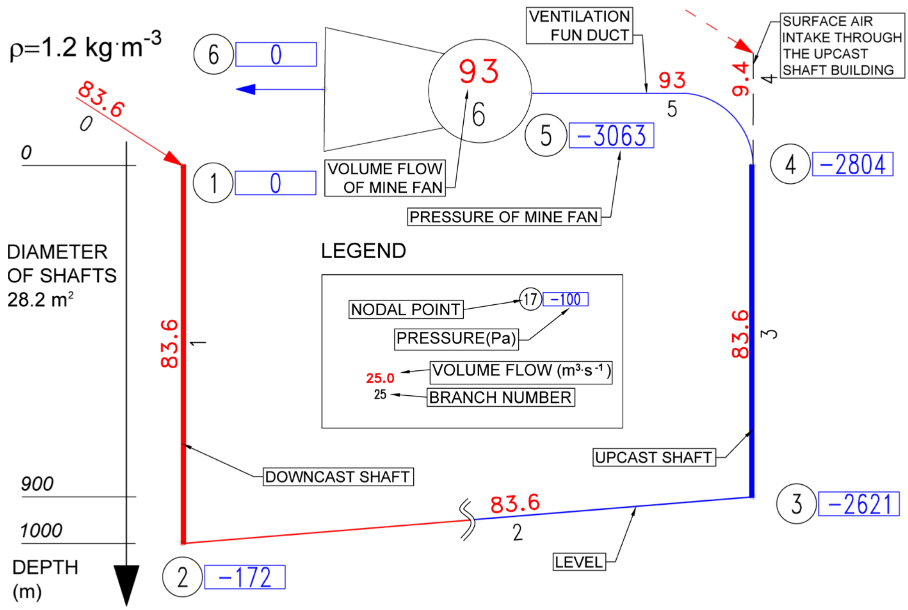

Fig. 2. Mine ventilation network diagram of the model – incompressible calculation of the default state

The main ventilation fan used in the model for the performed calculations is defined by a second-order polynomial that corresponds to the total pressure characteristic of a real fan [8] operating at an active mine, with control gear blades set to an angle of –30°. The functional form of the fan characteristic is given by the equation:

$$\Delta p_{fan} = 1840.148 + 36.029 \cdot Q_v - 0.246 \cdot Q_v^2 \ \text{[Pa]} \tag{2}$$

Where:

Δp_{fan} – total pressure rise across the fan [Pa],
Q_v – volumetric airflow through the fan [$m^3 \cdot s^{-1}$].

A graphical representation of the fan characteristic used in the model, along with the calculated operating point corresponding to the default state of the mine ventilation network, is shown in Fig. 3.

Let us assume that the emergency passage connected to the downcast shaft is 100 m in length. It is excavated in an arched profile with a clear cross-sectional area of 6.5 m^2 and connects to the shaft at a right angle (90°).

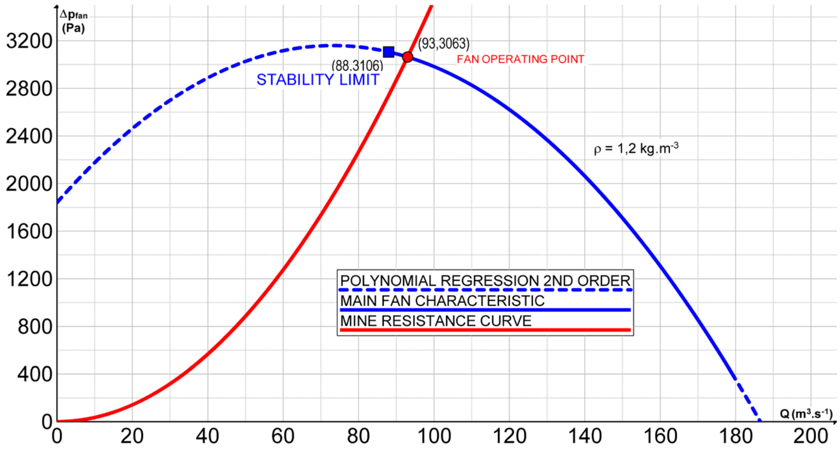

Fig. 3. Working characteristics of the main fan with the default operating point and stability limit

First, the **maximum permissible volumetric airflow** through the emergency passage must be calculated. According to Eq. (1):

$$Q_{\max} = 10 \cdot S_s = 10 \cdot 6.5 = 65.0 \ [\mathrm{m^3 \cdot s^{-1}}] \tag{3}$$

Where:

$Q_{\max}$ maximum permissible volumetric airflow through the emergency passage $[\mathrm{m^3 \cdot s^{-1}}]$

S_s – cross-sectional area of the emergency passage $[\mathrm{m^2}]$.

To simulate the closure of the fire cover on the downcast shaft in the mine ventilation network model, the original aerodynamic resistance of the downcast shaft (branch 1 in Fig. 2) is increased by the aerodynamic resistance of the emergency passage.

The total aerodynamic resistance of the emergency passage consists of two components: (i) the linear resistance of the passage itself and (ii) the local resistance due to the sudden expansion into the shaft.

To determine the magnitude of these aerodynamic resistances there can be used, for example, the Standardization Guidelines for Ostrava-Karviná coal district mine ventilation [35].

According to the Standardization Guidelines for Mine Ventilation in the Ostrava-Karviná Coal District [35], the specific aerodynamic resistance of a 100 m long arched crosscut is:

$$R_{100} = 0.06151 \ \mathrm{Pa \cdot s^2 \cdot m^{-6}}$$

The linear resistance of the passage R_p is:

$$R_p = l_p / 100 \cdot R_{100} = 100/100 \cdot 0.06151 = 0.06151 \ \mathrm{Pa \cdot s^2 \cdot m^{-6}} \tag{4}$$

where:

l_p – length of the emergency passage [m],

R_{100} – specific aerodynamic resistance of a 100 m long mine working $[\mathrm{Pa \cdot s^2 \cdot m^{-6}}]$.

In this study, the unit R_{100} represents the aerodynamic resistance of a 100 m segment of a mine working, as commonly used in ventilation calculations in the Ostrava-Karviná Coal District. For different lengths, the total aerodynamic resistance is calculated by multiplying R_{100} by the length in units of 100 m (e.g., 300 m = 3 × R_{100}).

It is also necessary to determine the local resistance coefficient for the sudden expansion of the airstream [11]. In the model, the emergency passage connects to the shaft at a right angle, and the mine air flows from a smaller cross-sectional area into a larger one. This transition involves both a directional change and an expansion of the airstream – analogous to the airflow transition from a fan outlet into a shaft. Such a configuration is characterized by experimentally derived local resistance coefficients, typically obtained from tests conducted in smooth pipelines. The values depend on the velocity profile around the curve and are summarized in TABLE 4.

TABLE 4

Values of the local resistance coefficient for sudden expansion, as a function of the cross-sectional area ratio $S_1:S_2$

Corner configuration	$\mathbf{S_1:S_2}$			
	1	**2**	**3**	**4**
No rounding of corners	1.3	4.1	10.0	**21.0**

where:

S_1 – expanded cross-section (shaft) [m^2],

S_2 – reduced cross-section (emergency passage) [m^2].

According to this table, the local resistance coefficient for a right-angled turn with a sudden expansion of the airstream from a 6.5 m^2 emergency passage into a 28.2 m^2 shaft results in a cross-sectional area ratio of:

$$\frac{S_1}{S_2} = \frac{28,2}{6,5} \approx 4,3$$

which corresponds to a **shock loss factor** of:

$$\xi = 21$$

Local transition resistance R_l according to Standardization Guidelines [35] is:

$$R_l = \frac{0.0612 \cdot \xi}{S_2^2} = \frac{0.0612 \cdot 21 / 6,5^2}{6.5^2} = 0.03 \text{ Pa} \cdot \text{s}^2 \cdot \text{m}^{-6} \tag{5}$$

where:

ξ – the shock loss factor for the sudden expansion,

S_2^2 – clear cross-section of the emergency passage [m^2].

The total aerodynamic resistance of the emergency passage R_{tot} is calculated as the sum of the minework aerodynamic resistance R_p and the local resistance of the transition to the shaft R_l:

$$R_{tot} = R_p + R_l = 0.091 \ [\text{Pa} \cdot \text{s}^2 \cdot \text{m}^{-6}] \tag{6}$$

where:

R_{tot} – total aerodynamic resistance of the emergency passage [$Pa \cdot s^2 \cdot m^{-6}$],

R_p – linear resistance of the passage $[\mathrm{Pa \cdot s^2 \cdot m^{-6}}]$,
R_l – local transition resistance $[\mathrm{Pa \cdot s^2 \cdot m^{-6}}]$.

The aerodynamic resistance of the downcast shaft after fire cover closure, denoted as $R_{sh_{cl}}$, is calculated as the sum of the original aerodynamic resistance of the downcast shaft R_{sh} (branch 1 in Fig. 2) and the total aerodynamic resistance of the emergency passage R_{tot}.

$$R_{sh_{cl}} = R_{tot} + R_{sh} = 0.08774 + 0.0246 = 0.11653\ [\mathrm{Pa \cdot s^2 \cdot m^{-6}}] \tag{7}$$

where:
$R_{sh_{cl}}$ – aerodynamic resistance of the downcast shaft after closure $[\mathrm{Pa \cdot s^2 \cdot m^{-6}}]$,
R_{tot} – original aerodynamic resistance of the downcast shaft (branch 1) $[\mathrm{Pa \cdot s^2 \cdot m^{-6}}]$,
R_{sh} – total aerodynamic resistance of the emergency passage $[\mathrm{Pa \cdot s^2 \cdot m^{-6}}]$.

This aerodynamic resistance replaces the aerodynamic resistance of branch 1 in the mine ventilation network model (TABLE 2), and the calculations were subsequently performed using the value of $R_{sh_{cl}} = 0.11653\ \mathrm{Pa \cdot s^2 \cdot m^{-6}}$ as determined by Eq. (7).

The output of the updated calculation is displayed in TABLE 5. The branch of the downcast shaft is highlighted, as its aerodynamic resistance has been replaced with this corrected value based on the emergency passage profile and transition conditions.

The mine ventilation diagram corresponding to this scenario is displayed in Fig. 4, and the results confirm the volumetric airflow in branch 1. Given a cross-sectional area of 6.5 $\mathrm{m^2}$ and a volumetric airflow of 76.94 $\mathrm{m^3 \cdot s^{-1}}$, the air velocity in the emergency passage is:

$$v = \frac{Q}{S} = \frac{76{,}94}{6{,}5} \approx 11{,}8\ \mathrm{m \cdot s^{-1}}$$

where:
v – air velocity $[\mathrm{m \cdot s^{-1}}]$,
Q – volumetric airflow $[\mathrm{m^3 \cdot s^{-1}}]$,
S – cross-sectional area $[\mathrm{m^2}]$.

This velocity exceeds the maximum permissible limit for safe personnel movement (10 $\mathrm{m \cdot s^{-1}}$), thus necessitating regulation measures to reduce airflow through the emergency passage.

TABLE 5

The output of the calculation for the fire cover closure on the downcast shaft

B	NP1	NP2	h1 [m]	h2 [m]	R $[\mathrm{Pa \cdot s^2 \cdot m^{-6}}]$	Q $[\mathrm{m^3 \cdot s^{-1}}]$	ρ $[\mathrm{kg \cdot m^{-3}}]$	Q_m $[\mathrm{kg \cdot s^{-1}}]$	ΔP_b [Pa]	P [W]	p_{inlet} [Pa]	p_{outlet} [Pa]
0	6	1	0.0	0.0	0.000000	76.94	1.200	92.33	0.0	0	0.0	0.0
1	1	2	0.0	1000.0	0.11653	76.94	1.200	92.33	665.1	51170.5	0.0	–665.1
2	2	3	1000.0	900.0	0.350000	76.94	1.200	92.33	2072.0	159423.8	–665.1	–2737.1
3	3	4	900.0	0.0	0.026190	76.94	1.200	92.33	155.0	11929.5	–2737.1	–2892.1
4	6	4	0.0	0.0	30.000000	9.51	1.200	11.41	2892.1	27494.6	0.0	–2892.1
5	4	5	0.0	0.0	0.030000	86.45	1.200	103.74	224.2	19381.8	–2892.1	–3136.3
6	5	6	0.0	0.0	0.000000	86.45	1.200	103.74	0.0	0	–3116.3	0.0

This velocity exceeds the maximum permissible limit for safe personnel movement (10 m·s^{-1}), thus necessitating regulation measures to reduce airflow through the emergency passage.

$$\Delta p_{fan} = A0 + A1 \cdot Q + A2 \cdot Q2 + A3 \cdot Q3$$

The coefficients used in this model are listed in TABLE 5a.

TABLE 5a

Polynomial coefficients and operating parameters of the main fan (branch 6)

Branch	***A0***	***A1***	***A2***	***A3***	Q_v [m^3·s^{-1}]	Δp_{fan} [Pa]	P_{useful} [kW]
6	1840,1	36,029	–0,246	0,00	86,45	3116,3	269,4

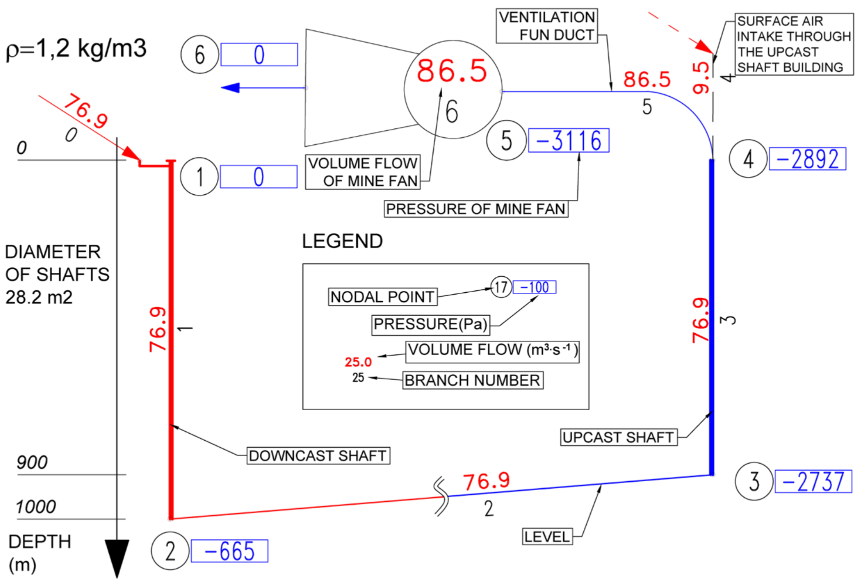

Fig. 4. Mine ventilation network diagram corresponding to the scenario with the fire cover closed on the downcast shaft

Fig. 5 displays the operating characteristics of the main fan, with the plotted operating point corresponding to the scenario after the closure of the fire cover on the downcast shaft. The graph clearly shows that the increase in aerodynamic resistance of the downcast shaft shifts the fan's operating point beyond the stability threshold. This condition indicates a potential instability in fan performance and therefore necessitates the implementation of corrective measures.

In the second step, it is necessary to verify whether a reduction in suction resistance on the upcast shaft will shift the operating point of the main fan back into the stable region. At the same time, it must be confirmed that volumetric air flowing through the emergency passage is reduced to a level that permits the safe evacuation of personnel and ensures at least the minimum required mine ventilation.

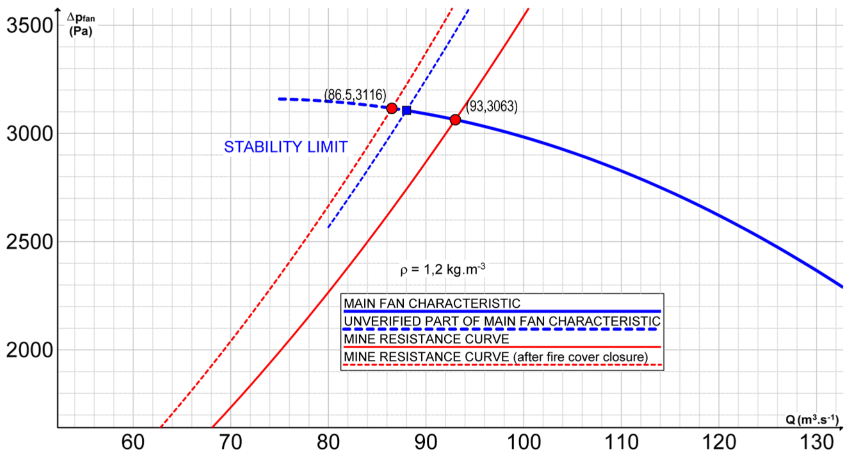

Fig. 5. Shift of the operating point of the main fan after the closure of the fire cover on the downcast shaft

The aerodynamic resistance of the suction branch (Branch 4) was reduced in the model to simulate the partial opening – or "unsealing" – of the ventilation structure (the upcast shaft) to a degree that allows approximately 60 $m^3 \cdot s^{-1}$ of air to enter the mine. This desired flow rate was achieved by adjusting the resistance parameters of the branch, not by imposing a fixed volumetric flow value.

If this adjustment does not return the fan's operating point to the stable zone or fails to reduce the airflow through the emergency passage below the specified maximum threshold, the resistance must be further decreased. Naturally, the airflow must not exceed the maximum value realistically achievable under operating conditions. The calculations should be iterated until both boundary conditions are satisfied.

The resulting values are presented in TABLE 6, the adjusted ventilation network configuration is shown in Fig. 6, and the new fan operating point is depicted in Fig. 7.

Based on the final outputs, it can be concluded that both conditions have been met.

The resulting volumetric airflow through the emergency passage is 64.7 $m^3 \cdot s^{-1}$, corresponding to an air velocity of 10 $m^3 \cdot s^{-1}$ – the maximum allowable limit for safe personnel movement.

TABLE 6

Output of the calculation for the scenario with the fire cover closed on the downcast shaft – resulting ventilation state

B	NP1	NP2	h1	h2	R	Q	ρ	Q_m	ΔP_b	P	p_{inlet}	p_{outlet}
			[m]	[m]	[$kg \cdot m^{-7}$]	[$m^3 \cdot s^{-1}$]	[$kg \cdot m^{-3}$]	[$kg \cdot s^{-1}$]	[Pa]	[W]	[Pa]	[Pa]
0	6	1	0.0	0.0	0.000000	64.66	1.200	77.59	0.0	0	0.0	0.0
1	1	2	0.0	1000.0	0.11653	64.66	1.200	77.59	469.7	30368.3	0.0	–469.7
2	2	3	1000.0	900.0	0.350000	64.66	1.200	77.59	1463.3	94613.7	–469.7	–1932.9
3	3	4	900.0	0.0	0.026190	64.66	1.200	77.59	109.5	7079.8	–1932.9	–2042.4
4	6	4	0.0	0.0	0.567340	60	1.200	72	2024.4	122546.2	0.0	–2042.4
5	4	5	0.0	0.0	0.030000	124.66	1.200	149.59	466.2	58115.5	–2024.7	–2508.6
6	5	6	0.0	0.0	0.000000	124.66	1.200	149.59	0.0	0	–2508.6	0.0

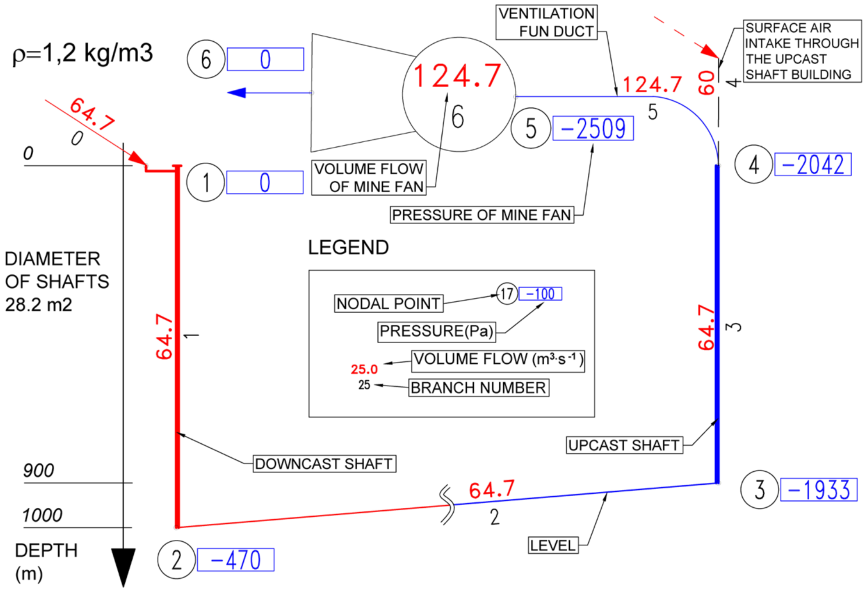

Fig. 6. Mine ventilation network diagram of the model showing the calculation scenario with the fire cover closed on the downcast shaft and reduced suction resistance on the upcast shaft

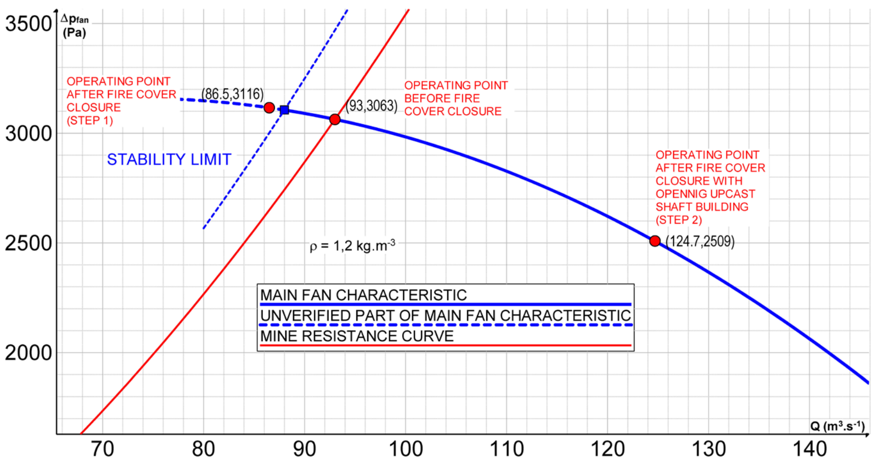

Fig. 7. Shift of the main fan operating point after closure of the fire cover on the downcast shaft and reduction of suction resistance on the upcast shaft

To achieve this state, the ventilation network had to be adjusted so that the main ventilation fan extracted approximately 60 $m^3 \cdot s^{-1}$ of air through the upcast shaft. This corresponds to about 48% of its total volumetric flow rate of 124.7 $m^3 \cdot s^{-1}$. This adjustment was implemented by reducing the aerodynamic resistance on the suction side, simulating partial unsealing of the upcast shaft building.

The characteristic of the fan at an air density of $\rho = 1.2\ \text{kg}\cdot\text{m}^{-3}$ is defined in **branch 6** by a second-degree polynomial, expressed by the following equation:

$$\Delta p_{fan} = A0 + A1 \cdot Q + A2 \cdot Q2 + A3 \cdot Q3$$

The corresponding coefficient values used in the model are:

TABLE 6a

Polynomial coefficients and operating parameters of the main fan (branch 6)

Branch	***A*0**	***A*1**	***A*2**	***A*3**	Q_v [$m^3 \cdot s^{-1}$]	Δp_{fan} [Pa]	P_{useful} [kW]
6	1840,1	36,029	–0,246	0,00	124,66	2508,6	312,7

The volumetric flow through the mine is then reduced from 83.6 $m^3 \cdot s^{-1}$ to 64.7 $m^3 \cdot s^{-1}$.

As a result of the applied measures, the volumetric airflow through the mine decreased from 83.6 $m^3 \cdot s^{-1}$ to 64.7 $m^3 \cdot s^{-1}$. However, it is difficult to conclusively assess whether this reduced airflow is sufficient under emergency conditions.

The adequacy of the resulting airflow at the time of the incident will depend on the specific reason for deploying the fire cover. It can be assumed that the primary objective of using a fire cover – while maintaining limited ventilation – would be to reduce the overall oxygen supply to the fire, thereby limiting combustion. A secondary objective may be to decrease airflow velocity in order to reduce the rate of fire propagation.

In such situations, some of the usual principles of maintaining standard airflow rates throughout the mine may become less relevant. The exact volume of airflow that is necessary to achieve the desired effect of the fire cover can only be determined at the moment such a measure is implemented during an actual emergency.

The procedure proposed above for determining the required amount of mine air is intended to demonstrate a methodological approach to this issue and to highlight the technical implications associated with the use of a fire cover – implications that must be considered in advance, before such a measure is activated in practice.

6. Discussion

As already stated in the Introduction, the presented model is intentionally simplified and does not account for temperature, humidity, or natural ventilation pressure. The primary aim was to propose a clear method ensuring the stable operation of the main mine fan under emergency conditions.

The volumetric airflow through the mine was reduced from 83.6 $m^3 \cdot s^{-1}$ to 64.7 $m^3 \cdot s^{-1}$ by applying the proposed adjustments. However, it remains difficult to determine whether this reduced airflow will be sufficient in the event of an actual mine fire.

The adequacy of the ventilation will depend on the specific circumstances that lead to the deployment of the fire cover. In most cases, the fire cover is used to limit the oxygen supply to the fire, reducing combustion potential. A secondary effect is the reduction of air velocity, which may help to slow the spread of flames and hot gases. Under such conditions, traditional requirements for maintaining nominal airflow throughout the mine may become less important.

Additionally, although more advanced methods such as CFD simulations or three-dimensional airflow modelling exist, they are limited by several practical constraints. These tools depend on highly accurate and detailed input data, which are rarely available during emergency situations. For instance, the pressure loss caused by the fire or the precise reduction in aerodynamic resistance due to increased suction cannot be reliably predicted in advance. Implementation of such tools in emergency planning would require extensive technical modifications to the ventilation infrastructure and could also pose significant economic challenges.

Ultimately, the practical applicability of this method can only be tested during an actual fire emergency. This would require direct measurement of ventilation parameters at several key locations: at the mine intake, inside the emergency passage, within the fan duct, and at the unsealed outlet of the upcast shaft.

7. Conclusion

This article presented a methodology for determining the necessary volumetric airflow through an emergency passage in the event of a mine fire that requires the closure of fire covers on downcast shafts.

The approach is based on a ventilation network model and focuses on compliance with safety regulations. While the legal requirement to define this airflow exists, no calculation procedure is provided by the current legislation. The method introduced here offers a practical and technically sound solution supported by explicit equations and fan operating characteristics. It is also more consistent with regulatory intent than current practice.

The proposed method consists of the following main steps:

- Determine the critical aerodynamic resistance of the mine, which governs the stable operation of the main fan.
- Define the minimum opening required to allow air entry into the mine after the closure of fire covers.
- Assess whether the combined resistance exceeds the critical limit, and if so, modify the suction path (in parallel with the downcast shaft) to stabilize the fan operation.
- Adjust the fan configuration to maintain airflow while keeping the system within its stable operational range.
- Ensure that the minimum required airflow is preserved to maintain safe and breathable conditions in the mine.

This method offers a structured approach for advance planning and preparedness. It may not fully eliminate the unpredictability of real fire scenarios, but it enables mine operators to meet regulatory obligations with a clear, defensible methodology.

References

[1] M. Tutak, J. Brodny, D. Szurgacz, L. Sobik, S. Zhironkin, The Impact of the Ventilation System on the Methane Release Hazard and Spontaneous Combustion of Coal in the Area of Exploitation – A Case Study. Energies **13** (18) (2020). DOI: https://doi.org/10.3390/en13184891

[2] A.V. Shalimov, Numerical modeling of air flows in mines under emergency state ventilation. Journal of Mining Science **47** (6), 807-813 (2011). DOI: https://doi.org/10.1134/S106273914706013X

[3] K. Wang, H. Hao, S. Jiang, Z. Wu, W. Cai, Z. Wang, Study on fire smoke flow characteristics in the ventilation network and linkage control system in coal mines. Fire and Materials **44** (7), 989-1003 (2020).
DOI: https://doi.org/10.1002/fam.2901

[4] M.C. Suvar, D. Cioclea, V. Arad, C. Lupu, N.I. Vlasin, Method for Improving the Management of Mine Ventilation Networks After an Explosion. Environmental Engineering and Management Journal **16** (6), 1373-1381 (2017).
DOI: https://doi.org/10.30638/eemj.2017.148

[5] N.-I. Vlasin, G.A. Gaman, C. Lupu, E. Ghicioi, E. Cozma, VENTMEX – portable software for mine ventilation characteristic curves,in: Geoconference On Science And Technologies In Geology. Exploration And Mining, Sgem 2014, **3**, 761-768 (2014).

[6] W. Dziurzynski, J. Kruczkowski, Validation of the mathematical model used in the Ventgraph programme on the example of the introduction of new headings to the ventilation network of mine. Archives of Mining Sciences **52** (2), 155-169 (2007).

[7] W. Dziurzyński, M. Grzywacz, J. Krawczyk, Analysis of Ventilation System and Assessment of Hazards in the Process of Progressing Liquidation of Workings in Mine 'S'. In: Proceedings of the 18^{th} Symposium on Environmental Issues and Waste Management in Energy and Mineral Production, 227-237 (2019).
DOI: https://doi.org/10.1007/978-3-319-99903-6_20

[8] A.K. Jha, Importance and Characteristics of Main Mechanical Ventilator, in: Selection of Main Mechanical Ventilators for Underground Coal Mines. Springer International Publishing (2017).
DOI: https://doi.org/10.1007/978-3-319-56859-1_1

[9] K. Gao, L. Deng, J. Liu, L. Wen, D. Wong, Z. Liu, Study on Mine Ventilation Resistance Coefficient Inversion Based on Genetic Algorithm. Archives of Mining Sciences **63** (4), 813-826 (2018).
DOI: https://doi.org/10.24425/ams.2018.124977

[10] M. Semin, L. Levin, Mathematical Modeling of Air Distribution in Mines Considering Different Ventilation Modes. Mathematics **11** (4), (2023). DOI: https://doi.org/10.3390/math11040989

[11] M. Bascompta, L. Sanmiquel, H.F. Anticoi, J. Oliva, Ventilation friction factor determination and comparison: Two case studies of potash mining. Journal of The Southern African Institute of Mining and Metallurgy **119** (10), 865-870 (2019). DOI: https://doi.org/10.17159/2411-9717/707/2019

[12] S. Gillies, H.W. Wu, Case Studies from Simulating Mine Fires in Coal Mines and Their Effects on Mine Ventilation Systems. In: Fifth Australasian Coal Operators Conference, 111-125 (2004).

[13] Z. Ouyang, G. Zhang, Q. Li, X. Lai, H. Qin, X. Zhao, X. Zhou, Study on the rock burst tendentiousness of coal under different gas pressures. Arabian Journal of Geosciences **13** (1), (2020).
DOI: https://doi.org/10.1007/s12517-019-4991-y

[14] X. Liu, X. Wang, E. Wang, X. Kong, C. Zhang, S. Liu, E. Zhao, Effects of gas pressure on bursting liability of coal under uniaxial conditions. Journal of Natural Gas Science and Engineering **39**, 90-100 (2017).
DOI: https://doi.org/10.1016/j.jngse.2017.01.033

[15] T.E. Kgarume, S.M. Spottiswoode, R.J. Durrheim, Statistical Properties of Mine Tremor Aftershocks. Pure and Applied Geophysics **167** (1-2), 107-117 (2010). DOI: https://doi.org/10.1007/s00024-009-0004-5

[16] J. Liu, M. Lin, L. Jin, G. Li, S. Ou, Y. Wang, T. Wang, M. Jueraiti, Y. Tian, J. Wang, Influence of Molasses on the Explosion and Decomposition Properties of the Coal Dust Deposited in Underground Mines. Energies **16** (6), (2023). DOI: https://doi.org/10.3390/en16062758

[17] V. Kostenko, O. Zavialova, S. Pozdieiev, T. Kostenko, V. Hvozd, Mechanism of development of coal dust continuous explosion in a network of mine workings. Rudarsko-Geološko-Naftni Zbornik **37** (1), 45-53 (2022).
DOI: https://doi.org/10.17794/rgn.2022.1.5

[18] X. Chen, R. Bi, J. Huang, W. Shan, J. Xiao, D. Wang, Experimental study on early prediction index gas for spontaneous combustion. Energy Sources, Part A: Recovery, Utilization, And Environmental Effects **46** (1), 7003-7017 (2024). DOI: https://doi.org/10.1080/15567036.2020.1746443

[19] M. Onifade, B. Genc, Spontaneous combustion of coals and coal-shales. International Journal of Mining Science and Technology **28** (6), 933-940 (2018). DOI: https://doi.org/10.1016/j.ijmst.2018.05.013

[20] R. Hansen, The Passive Fire Protection of Mining Vehicles in Underground Hard Rock Mines. Mining, Metallurgy & Exploration **38** (1), 609-622 (2021). DOI: https://doi.org/10.1007/s42461-020-00359-7

[21] A.A. Sidorenko, Endogenous fire hazard Kuzbass mines, Journal of Mining Institute **207**, 66-69 (2014).

[22] D.S. Hallman, Foamed backfilling for combatting mine fires. Environmental Geotechnics **9** (5), 310-317 (2022). DOI: https://doi.org/10.1680/jenge.19.00079

[23] M.I. De Rosa, C.D. Litton, Rapid Detection and Suppression of Mining Equipment Cab Fires. Fire Technology **46** (2), 425-435 (2010). DOI: https://doi.org/10.1007/s10694-007-0022-8

[24] S.-H. Tang, X.-P. Zhang, Q.-S. Liu, W.-Q. Xie, X.-L. Wu, P. Chen, Y.-H. Qian, Control and prevention of gas explosion in soft ground tunnelling using slurry shield TBM. Tunnelling and Underground Space Technology **113**, (2021). DOI: https://doi.org/10.1016/j.tust.2021.103963

[25] W. Dziurzynski, S. Nawrat, J. Roszkowski, W. Trutwin, Computer simulation of mine ventilation disturbed by fires and the use of fire extinguisher. Proceedings of the 6th International Mine Ventilation Congress, 389-393 (1997).

[26] Y. Hong, D. Li, Q. Wu, H. Xu, 3D Path Network Planning: Using a Global Optimization Heuristic for Mine Water-Inrush Evacuation. Computing and Combinatorics, 279-290 (2019). DOI: https://doi.org/10.1007/978-3-030-26176-4_23

[27] Z. Shao, M. Meyrieux, M. Kumral, Optimal junction localization minimizing maximum miners' evacuation distance in underground mining network. Mining Technology **132** (1), 41-54 (2023). DOI: https://doi.org/10.1080/25726668.2022.2159307

[28] Z. Fu-Bao, S. Bo-Bo, C. Jian-Wei, M. Ling-Jun, A New Approach to Control a Serious Mine Fire with Using Liquid Nitrogen as Extinguishing Media. Fire Technology **51** (2), 325-334 (2015). DOI: https://doi.org/10.1007/s10694-013-0351-8

[29] G. Zhang, S. Yuan, M. Deng, Fire extinguishing mechanism and application research of nitrogen injection displacement. In: International Mining Forum on Mine Safety and Efficient Exploitation Facing Challenge off the 21st Century, 1-5 (2010).

[30] A. Haghighat, K. Luxbacher, Tenability analysis for improvement of firefighters' performance in a methane fire event at a coal mine working face. Journal of Fire Sciences **36** (3), 256-274 (2018). DOI: https://doi.org/10.1177/0734904118767066

[31] B. Wang, Z. Rao, Q. Xie, P. Wolański, G. Rarata, Brief review on passive and active methods for explosion and detonation suppression in tubes and galleries. Journal of Loss Prevention in The Process Industries **49**, 280-290 (2017). DOI: https://doi.org/10.1016/j.jlp.2017.07.008

[32] V. Zubíček, V. Hudeček, M. Kubica, A Proposal of Rock Burst Control Measures at the Coalface No. 1 4064 at the Mining Plant 1, in OKD, A. S. Czech Republic, Inżynieria Mineralna **1** (1), (2020). DOI: https://doi.org/10.29227/IM-2020-01-17

[33] G. Pach, J. Sułkowski, Z. Różański, P. Wrona, Costs Reduction of Main Fans Operation According to Safety Ventilation in Mines – A Case Study. Archives of Mining Sciences **63** (1), 43-60 (2018). DOI: https://doi.org/10.24425/118884

[34] J. Linhart, Vliv důlních požárů na větrání. Záchranář **30** (6) 2-3 (1994).

[35] P. Prokop, P. Zapletal, Standardization guidelines for Ostrava-Karviná coal district mine ventilation. Ostrava (2013).

[36] Decree No. 22/1989 Coll. Of The Czech Mining Authority on Occupational Safety and Health Protection and Operational Safety During Mining Activities And Mining Of Unmined Minerals Underground (1989).

[37] W. Budryk, Pożary i wybuchy w kopalniach. Katowice. Wydawnictwo Górniczo-Hutnicze (1956).

[38] Z. Ogorek, L. Suchan, Zpráva č. 154 Termodynamické změny důlních větrů při požáru v horizontální chodbě, VVUU Ostrava (1976).

[39] W. Dziurzyński, Prognozovanie procesu przewietriania kopalni glembinowej w warunkach pozaru podzemnego, PAN Krakow (1998).

[40] OKD – Company profile. https://www.okd.cz/en/about-us/company-profile; 2012 [cited 25 June 2023].