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SEASON-ORIENTED MINE VENTILATION MODES ANALYSIS*

The paper presents the results of the data analysis conducted at Bereznyaki Mine-2 of Uralkali in summer and winter (during the air pre-treatment period). The findings show that when mine air heaters are operating thermal drop of ventilation pressure appears in air supply shafts. It causes "airlocks" in the shafts – a phenomenon that nearly stops the airflow in one of the shafts while increasing dramatically the airflow in the other (others) air intake shafts. As a result, mine air heaters in the shafts may stop running which provokes freezing of the mine shaft shoring.

The analysis of mine ventilation modes performed in summer and winter determined the factors affecting the occurrence of "airlocks" in the air supply shafts during air pre-treatment.

Keywords: *air preparation, mine air-heating installation, main ventilation instalation, resource conservation, automation system, natural draft*

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Introduction

The operation mode of the mine airing system and the stability of the ventilation process determine the safety of the underground mining workings [1–4]. Fresh air is supplied to the mine using the main mine fan (MMF), which operation is influenced by a large number of disturbing factors [5]. The volume of the incoming airflow is constantly changing, the capacity of the MMF is exceeded by 5–15% [6, 7]. Considering that up to one half of the total electricity consumption at an underground mining working is spent on ventilation [8], such a method for air supply is highly energy demanding.

The situation further complicates during the cold season when air heating becomes a necessity. The inertia of the ventilation process results in the need to heat the air up to a much higher level than required by the safety regulations: temperature of the air entering the mine shafts can reach +20–24 °C instead of the assigned +2 °C [9]. Therefore, ventilation during the cold season brings another problem – overspending of energy resources on the air heaters running.

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Table 1. Pressure values in the main mine fan and its capacity during the winter and summer experiments depending on different impeller rotation speeds (n_i)

Impeller speed, №	MMF capacity, Q_{MMF}, m^3/s		Difference between capacities, ΔQ_{MMF}, m^3/s	MMF pressure, h_{MMF}, Pa		Difference between pressures, Δh_{MMF}, Pa
	Summer experiment	Winter experiment		Summer experiment	Winter experiment	
1	408.14	405.2	2.94	2633.71	2712.52	–78.81
2	368.8	377.8	–9.0	2297.64	2393.8	–96.16
3	343.33	351.4	–8.07	2022.29	2098.62	–76.33
4	304.44	325.2	–20.76	1765.15	1800.5	–35.35
5	309.8	321.9	–12.1	1701.41	1722.05	–20.64
6	275.5	296.6	–21.1	1494.49	1525.92	–31.43
7	247.8	269.5	–21.7	1300.33	1260.16	40.17
8	224.88	242.4	–17.52	1065.22	1038.52	26.7
9	199.2	220.8	–21.6	866.88	833.57	33.31
Σ	**2681.89**	**2810.8**	**–128.91**	**15147.12**	**15385.66**	**–238.54**
Σ/*n*	**297.99**	**312.31**	**–14.32**	**1683.01**	**1709.52**	**–26.5**
Comment: No.1 – n_1 = 375 rpm; No.2 – n_2 = 350 rpm; No.3 – n_3 = 325 rpm; No.4 – n_4 = 300 rpm; No.5 (normal operation mode) – n_5 = 295 rpm; No.6 – n_6 = 275 rpm; No.7 – n_7 = 250 rpm; No.8 – n_8 = 225 rpm; No.9 – n_9 = 200 rpm						

The reduction of the capacity safety factor and the energy spent on the air heaters is only possible when it does not lead to emergencies, i.e. the reduction of the air intake, heat exchangers or the mine shaft freezing, etc. In this case, the ventilation process should be controlled in an automated mode. For this purpose, it is necessary to establish factors that significantly affect this process in summer (during the warm season) and during the air pre-treatment period in winter (during the cold season).

Body of the paper

One of the essential factors significantly influencing the ventilation process is the natural draft (ND) and its direction in a mine [10–14]. Natural draft and its direction depend on the parameters of the fresh air entering the mine shafts, mainly, the air temperature. If the temperature of the intake air is below zero the analysis of the factors influencing the ventilation process should consider the air pre-treatment process. However, in this case, the process of air distribution between the mine shafts is expected to be different during summer and winter seasons.

Two experiments were held at the same mine (Bereznyaki Mine 2 of Uralkali) using the same MMF operating modes but at different times of the year: in summer (in June, the outdoor temperature is +21.8 °C) and in winter when air heaters are running (in February, the outdoor temperature is –2.1 °C). The results of the experiments are presented in [5].

During the summer experiment, nine measurements of the MMF pressure at different level of impeller speed (n_i) were made. The same measurements were made during the winter experiment. The duration of each of the experiments was 20 minutes.

Comparative assessment of research results is given in **Table 1**.

The analysis of the data presented in Table 1 shows that with high rotation speed (rows №1-3) the MMF capacity Q_{MMF} in summer and winter experiments differs slightly: the maximum difference ΔQ_{MMF} between Q_{MMF} values is about 2.5%. The difference Δh_{MMF} between MMF pressure values h_{MMF} at the same rotation speeds is about 4%.

However, as the MMF impeller speed decreased, the difference ΔQ_{MMF} between summer and winter capacity values Q_{MMF} increased. In each of the experiments, the difference amounted almost 11% with the rotation speed of n_9 = 200 rpm (row №9). The difference Δh_{MMF} between the MMF pressure values did not significantly change in percentage terms.

However, with the decrease of the MFF impeller speed to the level of n_7 = 250 rpm (row №7), the summer value $h_{MMF(sum)}$ has increased significantly compared to the winter value $h_{MMF(win)}$. A similar pattern for the difference Δh_{MMF} remained up to the minimum rotation speed level of n_9 = 200 rpm (row №9).

Analysis of the ratio of total pressure values (row Σ) and average pressure values (Σ/n) shows that the MMF pressures in summer and winter experiments differ by less than 2%. However, the difference in MMF capacity ΔQ_{MMF} in summer and winter experiments is as high as 9%.

The time spent on each of the experiments was only about 20 minutes, thus the natural draft in a mine could not change significantly during the experiment. However, the results of summer and winter experiments indicate that changing the MMF operating modes led to different changes in capacity Q_{MMF} and pressure h_{MMF} in summer and winter. This fact illustrates that mine ventilation processes during summer and winter differ due to some factors associated with the need for additional air pre-treatment during winter.

It should be noted that the air temperature supplied to the mine shafts during winter and summer experiments differed significantly (in June the temperature in the Urals is usually above zero, while in February the air temperature rarely rises above zero). Therefore, the natural draft between the shafts during these periods should differ significantly, yet the observations did not show that. Thus, it can be assumed that the air distribution between the shafts, in addition to the MMF pressure and the natural draft, is affected by some additional factors arising in the air supply shafts during air pre-treatment.

In [14] one can find a method for calculating the natural draft and its direction (h_e), as well as the air drag in a mine (R_{mine}). The calculations require the MMF measurements at different capacity values as an input. Hence, the data shown in Table 1 can be used to calculate these values.

According to [14], the value of the natural draft is calculated using the following formula:

$$h_e = \overline{h_{MMF}} - R_{mine}\overline{Q^2_{MMF}}, \qquad (1)$$

Hereinafter, the bar over a variable means that this is an average value of the variable calculated based on empirical data.

The value of the air drag in a mine is determined by the formula:

$$R_{mine} = \frac{\overline{Q^2_{\text{MMF}} h_{\text{MMF}}} - \overline{Q^2_{\text{MMF}} h_{\text{MMF}}}}{\overline{Q^4_{\text{MMF}}} - \left(\overline{Q^2_{\text{MMF}}}\right)^2}. \qquad (2)$$

The results in **Table 2** show the calculated natural draft h_e and air drag in a mine R_{mine} obtained from the data presented in Table 1.

The results revealed that at the same mine with the same MMF operation modes, the natural draft in the summer experiment ($h_{\text{e(sum)}}$) = 406.1 Pa) is more than 5 times greater than it was during the winter experiment ($h_{\text{e(win)}}$ = 75.99 Pa). The values of the air drag in a mine differ significantly (by 18.5%) as well. At the same time, as mentioned above, the data in Table 1 show that the MMF capacity and pressure during the winter and summer experiments differ slightly.

According to [15, 16] the most of the air drag (about 80%) in a mine occurs in the mine shafts and the main workings branching out from the shafts. Since the time difference between summer and winter experiments is less than 1 year, significant changes in the parameters of the mine shafts and the main mine workings could not occur during this period. In this case, following the formula (1), if the difference between h_{MMF} values and Q_{MMF} values is insignificant and the value of the air drag in a mine is practically invariable, then the following inequality is observed:

$$h_{\text{MMF}} = h_{\text{e(sum)}} + R_{mine}Q^2_{\text{MMF}} \neq h_{\text{MMF}} = h_{\text{e(win)}} + R_{mine}Q^2_{\text{MMF}}.$$

Hence, some other factors affecting the air distribution process in a mine are not yet considered in the formula (1).

The formulas given in [17] make it possible to determine with sufficient reliability the natural draft in a mine while the MMF is not operating. These formulas were used to calculate the natural draft during the summer and winter experiments. The results are: summer natural draft $h'_{\text{e(sum)}}$ = 431.23 Pa, winter natural draft $h'_{\text{e(win)}}$ = 143.20 Pa. The theoretical natural draft value $h'_{\text{e(sum)}}$ in summer experiment is greater than the empirical value $h_{\text{e(sum)}}$ by 5.8%, and in the winter experiment, the theoretical natural draft value $h'_{\text{e(win)}}$ is 2 times greater than the empirical value $h_{\text{e(win)}}$.

Based on these findings, it can be concluded that the MMF functioning during the winter season is significantly influenced not only by the natural draft but also by some other factors produced by the air pre-treatment process in the air intake shafts.

In this case, the formula (1) for the MMF pressure calculation should be changed so that both the natural draft (h_e) and some other type of draft are taken into account:

$$h_{\text{MMF}} = \tilde{h}_e + h_e R_{mine} Q^2_{\text{MMF}},$$

where the additional summand $\tilde{h}_e$ is the value caused by the air pre-treatment process in winter.

Thus, the problem is to clarify the meaning and estimate the value of the value ($\tilde{h}_e$).

For this purpose, a new model was developed that imitates the air pre-treatment system and the air shaft.

The heated air from the mine calorific facility enters the air intake shaft through the calorific shaft (**Fig. 1a**). Apart from the heated air, cold air leaks into the air intake shaft that leads to infiltration. Air infiltration is the process of cold air intake through the openings in the pithead building caused by the mine depression (pressure drop). As a result, there are problems in the air pre-treatment process: capacity regulation of the mine calorific facility changes depending on the temperature and volume of the intake air.

Table 2. The results of calculating the natural draft and the air drag in a mine during summer and winter experiments

Time of the experiment	Parameter			
	h_e, Pa	R_{mine}, (N·s^2)/m^8	h_{low}, Pa	h_{high}, Pa
Summer experiment $h_{\text{e(sum)}}$	406.1	0.01374	386.77	425.44
Winter experiment $h_{\text{e(win)}}$	75.99	0.01686	66.80	85.18

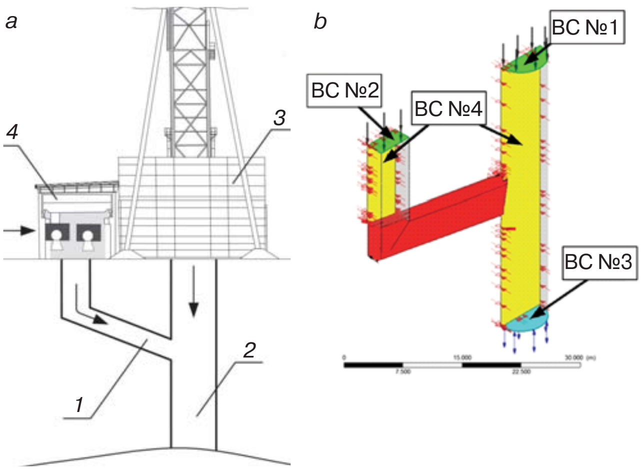

Fig. 1. The process of heated air supply from the mine calorific facility to the air intake shaft:
a – surface complex of the mine calorific facility (general view); *b* – boundary conditions of the system model; *1* – calorific shaft; *2* – air intake shaft; *3* – pithead building; *4* – mine calorific facility; BC – boundary conditions

The following boundary conditions (Fig. 1b) were assumed in the model:

Boundary condition № 1 – infiltration (inleakage) of the outside air through the pithead building with the parameters: velocity 2 m/s; temperature –36 °C.

Boundary condition № 2 – air supplied to the mine calorific facility with the following parameters: velocity 10 m/s; temperature –36 °C.

Boundary condition № 3 – air pressure in the pit-bottom hole: 101325 Pa.

Boundary condition № 4 – symmetry between the calorific shaft and the air-intake shaft.

Air parameters values used for the calculations were determined in [9] based on the regulations and experimental studies conducted at the mines.

The specified in the mathematical model boundary conditions made it possible to determine the air flow velocity in the calorific shaft (**Fig. 2a**). Figure 2 shows that the air flows velocity in the calorific shaft is distributed unevenly. In the lower part of the channel air flow velocity is much higher than in its upper part. The reason for this is the geometry of the calorific shaft.

The distribution of the temperature field in the shaft is shown in Fig. 2b.

Thus, problems of uneven air heating arise even before the air is supplied to the air intake shaft.

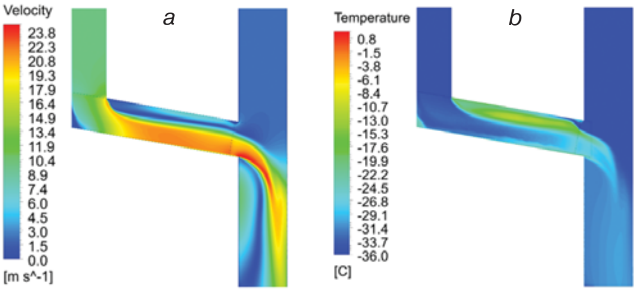

Fig. 2. Results of the air distribution simulation in the calorific shaft:
a – air velocity distribution; *b* – air heat flows distribution

When modelling the process of air distribution in the air supply shaft during the air pre-treatment period, it is necessary to consider that the shaft is reinforced. The developed model contains all reinforcement elements and differs from the previous models that treated a shaft as a hollow cylinder (**Fig. 3**).

The simulation confirmed that the velocity of the air flows differs along the cross-section of the shaft (Fig. 3a) and the temperature distribution is uneven (Fig. 3b). There are areas with cold air. As the cold air moves down the shaft, it does not mix with heated airflows but moves further slightly increasing its temperature.

As the temperature of the air coming from the air heater increases from 5 to 9 °C (**Fig. 4**) the distribution of the heated air along the shaft does not change significantly: the temperature in cold air regions slightly increases. Consequently, only considerable temperature increase of the air supplied through the air heater will ensure the required temperature distribution in "unheated" areas where the temperature is equal or close to the critical level (+ 2 °C). However, in this case, the supplied air

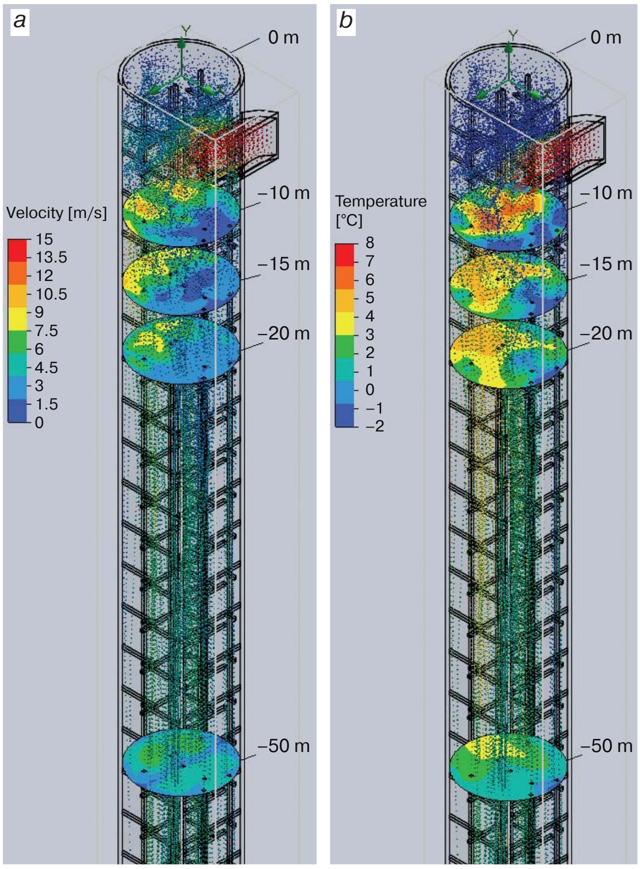

Fig. 3. Results of the air distribution simulation in the air intake shaft during the air pre-treatment process:
a – air flows velocity distribution; *b* – air flows temperature distribution

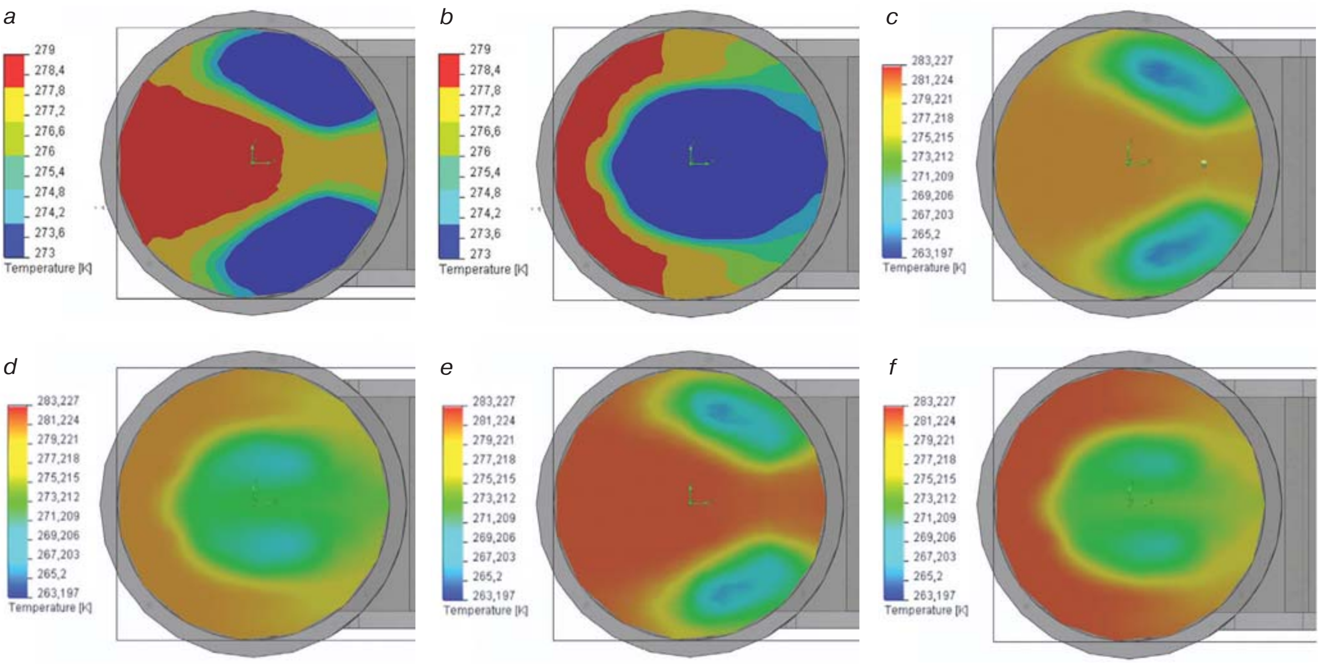

Fig. 4. Temperature field distribution in a shaft:
a, *c*, *e* – at the level of –15 meters; *b*, *d*, *f* – at the level of –30 meters, with different temperatures of the air coming in a shaft from the air heater: *a*, *b* – 5 °C; *c*, *d* – 7 °C; *e*, *f* – 9 °C

will be “overheated” significantly above the required temperature value.

The presence of air flows with different temperatures in a shaft will result in a thermal drop of ventilation pressure – “natural draft inside the shaft”.

The problem of airlocks in air supply shafts is described in [17]. This phenomenon that nearly stops the airflow in one of the shafts while increasing dramatically the airflow in the other (others) air intake shafts. Thus, neighboring air supply shafts may be exposed to air in the volume not designed for the shaft capacity, which may lead to failure of the air pre-treatment system. As practice shows, the only way to break the airlock is by forced multiple passages of a skip and/or a cage through the blocked air section.

Airlocks in the air supply shafts appear only when air heaters are running during the heating season [17], thus it can be assumed that the cause of this negative phenomenon is a “natural draft inside a shaft”.

Conclusions

Air drag in a mine can be estimated at any mine via an experimental study of the MMF. In the cold season, the value of the air drag in a mine can be determined concerning the “natural draft inside a shaft”, which occurs due to the air heaters operation during the air pre-treatment period.

These steps enable the calculation of the required operation mode for the air heaters and the MMF in advance with regard to the changing parameters of the outdoor air entering the mine shafts. The characteristics of the air can be obtained from meteorological forecasts that have high accuracy in a short term [18, 19]. Having predicted the operation mode of the MMF and air heaters (during the air pre-treatment period), it is possible to perform air ventilation even in an automated mode with minimal energy consumption and without “air plugs” in the air shafts and related consequences.

The results of this research can be used in conjunction with systems of energy data monitoring and analysis in case of the industrial energy savings [20–23]. Such integration of information management and analytical component is a part of digital based EMS (energy management system) of mining enterprises.

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