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Artem V. Zaitsev, Mikhail A. Semin, Oleg S. Parshakov
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Features of the thermal regime formation in the downcast shafts in the cold period of the year

Artem V. ZAITSEV, Mikhail A. SEMIN, Oleg S. PARSHAKOV✉
Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russia

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Abstract. In the cold period of the year, to ensure the required thermal regime in underground mine workings, the air supplied to the mine is heated using air handling systems. In future, the thermodynamic state of the prepared air flow when it is lowered along the mine shaft changes due to the influence of a number of factors. At the same time, the processes of heat and mass exchange between the incoming air and its environment are of particular interest. These processes directly depend on the initial parameters of the heated air, the downcast shaft depth and the presence of water flows into the mine shaft. Based on the obtained experimental data and theoretical studies, the analysis of the influence of various heat and mass transfer factors on the formation of microclimatic parameters of air in the downcast shafts of the Norilsk industrial district mines is carried out. It is shown that in the presence of external water flows from the flooded rocks behind the shaft lining, the microclimatic parameters of the air in the shaft are determined by the heat transfer from the incoming air flow to the underground water flowing down the downcast shaft lining. The research results made it possible to describe and explain the effect of lowering the air temperature entering the underground workings of deep mines.

***Key words*:** air handling system; air parameters; temperature distribution; downcast shaft; relative humidity; water flow; mathematical modeling

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Introduction. In the cold period, to prevent freezing of the air supply workings and protect miners from colds, the air entering the underground mine workings is heated [12]. According to the requirements of the current Federal Standards and Safety Rules for mining and processing of solid minerals, the incoming air must have a temperature of at least 2 °C. In this regard, air handling systems are used to form and maintain the required air temperature in the downcast shafts of mines [1, 4, 5, 13, 17].

Due to the use of the air handling system on the surface, the parameters of the incoming air undergo changes. As a result, during the cold period, the air temperature rises, and its humidity decreases. Thus, in the cold period, the microclimatic parameters of the air in the initial section of the shaft near its mouth depend not only on atmospheric conditions, but also on the air handling system parameters. In the future, the air parameters when moving down the downcast shaft change due to its hydrostatic (or adiabatic) compression, as well as heat and mass exchange with the shaft lining and the surrounding rock mass [6, 7]. At the same time, as practice shows and based on the existing literature [3, 9], the main factor determining the air temperature distribution in a deep shaft is hydrostatic compression, which leads to an increase in air temperature with depth. When air moves down the shaft in the field of gravity, it is significantly heated, which is well described by the linear law of air temperature change along the depth of the shaft. However, the results of experimental measurements carried out by specialists of the Mining Institute of the Ural Branch of the Russian Academy of Sciences (RAS) with the participation of the authors of the article in the downcast shafts of the Norilsk Industrial district deep mines during the cold period showed that the temperature of the incoming air decreases when it is lowered along the shafts. Thus, in the cold period, the thermal regime formation in the downcast shafts can significantly depend not only on the hydrostatic compression of air, but also on other heat and mass transfer processes.

In this regard, this article attempts to analyze the influence of various heat and mass transfer processes on the thermodynamic state of air moving through the downcast shaft. This study is

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important for understanding the patterns of microclimatic air parameters formation in deep mines and for developing measures to manage these parameters.

Research. In 2019-2020, the specialists of the Mining Institute of the Ural Branch of the RAS conducted complex ventilation and temperature-humidity surveys at several mines of the Norilsk Industrial district. One of the main stages of surveys was a detailed study of the aerodynamic and microclimatic parameters of the air in the downcast shafts and shaft bottoms of the mines [15]. During the experimental work, the air parameters in various sections of the mine shafts, including temperature and relative humidity, were measured. The Fluke 971 thermal moisture tester (relative measurement errors of temperature ± 0.5 °C; humidity ± 5.0 %) and Kestrel 5500 (relative measurement errors of temperature ± 0.5 °C; humidity ± 2.0 %) were used for experimental measurements.

Full-scale measurements were performed in the cold period at the following points: at the downcast shaft mouth at the level of air mixing (below the interface of the channel with the shaft by 20-30 m), entering through the head house and the heating channel; at the junction of the downcast shaft with the mine workings of the first underground level.

Table 1 shows the parameters of the downcast shafts of the studied deep mines and the parameters of the air entering through the shafts. All the shafts under consideration are equipped with air handling systems.

Table 1

Parameters of the downcast shafts and the air coming through it

Parameter	Downcast shafts						
	mine 1				mine 2		
	1	2	3	4	1	2	3
The length of the shaft section (the distance between two points), m	799	851	525	738	560	401	430
Diameter of the downcast shaft, m	8.0	8.0	6.5	6.5	8.0	6.0	8.0
Shaft cross-section area, m^2	50.2	50.2	33.2	33.2	50.2	28.3	50.2
The amount of air passing through the shaft, m^3/s	224.7	214.4	184.1	241.4	240.0	253.9	450.1
Air temperature at the shaft mouth, °C	23.5	33.9	20.0	18.8	22.8	12.0	18.3
Relative humidity at the shaft mouth, %	8.1	5.2	6.7	7.3	23.3	17.1	11.2
The air temperature in the shaft bottom, °C	20.2	20.3	18.4	16.9	16.0	11.1	14.4
Relative humidity in the shaft bottom, %	12.3	15.3	14.5	17.5	41.8	22.9	24.1

It can be seen from Table 1 that for all downcast shafts, the air temperature recorded at the points of connection of the shafts with the first underground level is lower than the air temperature measured at the mouth of the shafts. At the same time, the relative humidity of the air, on the contrary, increases as the air descends along the shaft. In the warm period, when the air handling system was not used, the results of similar measurements in the studied shafts of the Norilsk industrial district mines showed the opposite – the air movement down the downcast shaft is characterized by air heating due to hydrostatic compression and a decrease in relative humidity [7, 13].

Traditionally, the following main factors and thermodynamic processes are distinguished that determine the air temperature formation moving down the downcast shaft [7]: the initial temperature and humidity of the air at the shaft mouth; heat exchange between the rock mass surrounding the shaft and the air passing through the shaft; hydrostatic compression and heating of the air as it moves down the shaft; mass exchange processes (especially related to moisture exchange processes).

The heat exchange between the rock mass surrounding the shaft and the air passing through the shaft is usually considered negligible for mine shafts operated for a long time, due to the formation of a so-called “heat leveling jacket” in the surrounding rock mass [2]. In some studies [11, 21, 22], this factor, nevertheless, is considered important and requires consideration even for downcast shafts operated for a long time.

When air was lowered along the shaft, as a result of the action of hydrostatic compression alone, it would be heated, which is described by the linear law of air temperature change along the depth of the shaft – approximately 1°C for every 130 m of depth increase. Taking into account the depth of the above-mentioned downcast shafts, the minimum air heating should have reached 4 °C (shaft 2 of mine 2), and the maximum – 8 °C (shaft 2 of mine 1). Due to the fact that the results of experimental studies indicate the opposite effect of air cooling, hydrostatic compression is not the only significant factor in the air temperature formation along the depth of the shaft.

To carry out a quantitative assessment of the various processes of heat and mass transfer influence in the downcast shafts, additional information was obtained about the existing water flows in the shafts. Based on the hydrogeological survey of the downcast shafts of mines, specialists obtained the total average hourly inflows of natural and industrial water into the sumps: mine 1, shaft 1 – 1.5, shaft 2 – 1.8, shaft 3 – 1.5, shaft 4 – 1.7 m^3/h; mine 2, shaft 1 – 0.4, shaft 2 – 0.2, shaft 3 – 6.4 m^3/h. The average water temperature is 7 °C, it is caused by the natural geothermic gradient of the rock mass at the depths of aquifers.

There are water flows in the studied shafts, while the water temperature differs from the air temperature. Underground water that penetrates through the leaky concrete lining into the shaft space flows down the walls and interacts with the air flow moving along the shaft. This interaction is expressed both in the form of heat exchange of warmer air with a less warm water film on the shaft wall, and in the form of mass exchange – some mass of water at the boundary of the water layer with air can evaporate, leading to an increase in the moisture content of the air. Some part of the water can be torn off by the air flow and be present in it in the liquid state in the form of small drops. In the cold period, the initial humidity of the air entering the downcast shaft is relatively small, and therefore the process of water evaporation flowing down the shaft lining and increasing the moisture content of the air in the shaft should proceed intensively.

In order to fully investigate the influence of heat and mass exchange of air with underground water penetrating into the shaft on the air temperature along the depth of the downcast shafts, in addition to the conducted field studies, a theoretical analysis was performed.

Mathematical modeling. Full-scale measurements of the microclimatic parameters of the air entering the mine workings and the results of the mine shafts survey made it possible to carry out parametric support of mathematical models of heat and mass transfer processes in the downcast shafts with the setting of initial and boundary conditions.

First of all, a generalized mathematical formulation of the problem of heat and mass transfer in a downcast shaft with arbitrary geometric properties and physical parameters of air is made. Within the framework of such a statement, a vertical shaft was considered, along which air descends. The air flow in the shaft is considered stationary. The air descending along the shaft exchanges heat with various sources of heat in the shaft that have a constant temperature: the shaft concrete lining and ground water that got into the shaft from the rock mass through defects (cracks) in the concrete and flowing down the shaft lining. Their influence was taken into account on average by means of uniform temperatures and heat transfer coefficient on the shaft wall, which were selected on the basis of available empirical data. The thermal effect of groundwater consisted in the heat of the phase transition released in the airspace as a result of evaporation of the part of water, as well as in the convective heat flow to the air with the help of small water droplets that break off from the water film on the shaft lining and enter the air flow.

The energy balance equation of a certain small volume of air when it passes a vertical distance Δx is written as follows [23]: $\Delta Q = \Delta I + \Delta A$, i.e. the heat ΔQ, entering or leaving the air goes to increase its heat content ΔI and perform the work of the pressure forces ΔA to compress the air. When detailing the energy values included in the equation, it takes the form [16]:

$$\rho_a c_a \Delta T = \frac{4\alpha\Delta x}{Dv}(T_h - T) - \rho_a L \Delta m_1 + \rho_a c_w (T_h - T)\Delta m_2 + P\Delta\rho, \quad (1)$$

where ρ_a is the air density, kg/m^3; c_a is the specific heat capacity of the air, J/(kg·°C); L is the specific heat of water condensation, J/g; ΔT is the change in air temperature when moving by Δx, °C; α is the coefficient of non-stationary heat exchange with heat sources (lining and water flows [10], W/(m^2·°C); v is the air flow rate in the shaft, m/s; T_h is temperature of heat sources, °C; T is the average cross-section air temperature, °C; $\Delta m_1 > 0$ is the amount of evaporated moisture due to changes in the thermodynamic parameters of the air at the section Δx, g/kg; $\Delta m_2 > 0$ is the amount of droplet moisture captured by the air flow from the water film, g/kg; c_w is the specific heat capacity of water, J/(g·°C); P is total pressure, Pa; $\Delta\rho$ is change in air density, kg/m^3.

The parts of the equation $\frac{4\alpha\Delta x}{Dv}(T_h - T)$, $\rho_a L\Delta m_1$, $\rho_a c_w(T_h - T)\Delta m_2$ and $P\Delta\rho$ characterize the heat exchange of air with the wet shaft lining, the heat of moisture evaporation from the shaft wall, convective heat transfer due to the separation of droplet moisture and hydrostatic heating of the air when it is lowered down, respectively.

The total pressure in the depth of the shaft varies according to a linear law:

$$P = P_0 + \rho_0 q x,$$

where P_0 is the total pressure on the surface, Pa; ρ_0 is the air density on the surface, kg/m^3; q is the acceleration of gravity, m/s^2; x is the coordinate along the axis of the shaft, measured from its mouth down, m.

The air density is calculated by the formula:

$$\rho_a = \frac{29P - 0.11\varphi(479 + (11.52 + 1.62T)^2)}{8314(T + 273)}, \quad (2)$$

where φ is the relative humidity of the air, %.

The change in the moisture content of the air m occurs only due to the moisture evaporation $\Delta m = \Delta m_1$.

As the air descends through the downcast shaft, its relative humidity changes according to a known law:

$$\frac{\varphi}{100\ \%} = \frac{Pm}{P_s(0.622 + m)}, \quad (3)$$

where P_s is the pressure of saturated water vapor (Pa), calculated by the formula:

$$P_s = 611 \exp\left(\frac{17.5T}{T + 241.2}\right).$$

It follows from equations (3) and (4) that the change in the moisture content along the depth of the shaft Δm can be determined based on changes in temperature, pressure and relative humidity of the air.

If now, in the simplest case, we consider $\Delta x = H$ and substitute into equation (1) the values of the measured temperatures and relative humidity of the air, as well as the known numerical expressions for the physical properties of water and air, then for the shaft 1 of the mine 1 we get:

$$-1.26 \cdot 1005 \cdot 3.3 = \frac{4 \cdot 11.15 \cdot 799}{8 \cdot 4{,}47}(7 - 21.85) - 1.25 \cdot 2258 \cdot 0.0334 + 1.26 \cdot 4.2(7 - 21.85)\Delta m_2 +$$

$$+ 106224 \cdot 0.129. \quad (5)$$

The values equal to the arithmetic mean of the corresponding physical parameters of the air measured at the beginning and end of the shaft section were taken as the average barometric pressure, average temperature and average air density on the shaft section. The temperature of 7°C was used as the temperature of the T_h shaft wall. The change in air density was calculated from the formula (2)

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from the known values of temperature, pressure and humidity at the beginning and end of the section [8, 14, 19].

The coefficient of heat transfer of air and the wet shaft wall was calculated according to the formula of A.N.Shcherban [18] with a coefficient k = 1.5, taking into account the intensification of heat transfer due to the presence of a water film on the surface of the shaft wall [20]. As a result of solving equation (5) with regard to Δm_2, it is obtained that the amount of moisture passing from the water film into the air medium and remaining in the liquid phase is 38.5 g/kg. At the same time, the amount of moisture passing from the water film into the air medium due to evaporation is 0.0335 g/kg.

Table.2 shows the ratio of the influence of various heat and mass transfer processes occurring in the studied shafts in the formation of the final air temperature in the shaft bottom of the mine. Influence I was calculated as the ratio of the heat contributed or diverted from the system by the factor under consideration to the change in the internal energy of the system (air flow):

$$I = \frac{W_i}{\rho_a c_a \Delta T} \cdot 100\ \%,$$

where W_i is the heat from the i-th thermal factor.

Table 2

The ratio of the influence of heat and mass transfer processes on the air temperature in the shaft bottoms of mines

Factor	Influence of heat exchange processes, %						
	Shafts of the mine 1				Shafts of the mine 2		
	1	2	3	4	1	2	3
Heat exchange with wet shaft wall	332.5	127.2	489.5	480.0	100.2	243.2	88.9
Moisture evaporation from the wet shaft wall	1.9	1.1	18.1	18.7	13.0	13.7	10.3
Convective heat transfer due to the separation of droplet moisture	78.6	82.8	23.8	106.7	122.1	419.2	169.2
Hydrostatic air heating	–313.0	–111.1	–431.4	–505.4	+135.2	–576.1	–168.4

Note. Plus means that the factor in consideration contributes and assists the actually observed decrease in air temperature with depth, and minus means that the factor, on the contrary, is aimed at increasing the air temperature with depth, i.e. there is a counteract to the actually observed decrease in air temperature.

In total, four thermal factors taken into account by the model (1) and listed earlier were considered: heat exchange with wet shaft wall, moisture evaporation from the wet shaft wall, convective heat transfer due to the separation of droplet moisture, hydrostatic heating of air. The total effect of all processes for each of the shafts is 100 %, i.e. the change in air temperature is completely due to the action of the processes.

From the Table 2 it follows that for mine 1, the key factors are heat exchange with the shaft wall and hydrostatic heating of the air due to its compression. They have a multidirectional effect and almost completely compensate for the influence of each other. Because of this, the factor of convective heat transfer due to the separation of droplet moisture, despite the fact that its relative contribution is several times less, also becomes significant. For mine 2, the factor of convective heat transfer due to the separation of droplet moisture is more significant – this is due to the fact that the depth of the shafts of mine 2 is less than mine 1, it is also due to high temperature differences in shafts 1 and 3 and high air flow rate in shaft 2. For the shafts of both mines, the effect of moisture evaporation from the wet shaft wall on the air temperature in the shaft is negligible.

Conclusion. The results of full-scale measurements of the temperature and relative humidity of the air entering through the downcast shafts during the cold period are presented. It is shown that when the heated air is lowered along the shaft, it cools due to the significant influence of heat and mass transfer processes. The mathematical formulation of the problem of heat and mass transfer of

incoming air with its surrounding environment is presented. Calculations of heat distribution in the downcast shaft are made taking into account the influence of various thermal factors. The ratio of the influence of various heat and mass transfer processes occurring in the downcast shafts on the air temperature distribution along the depth of the shaft is given.

The developed and parameterized mathematical model made it possible to describe and explain the effect of lowering the air temperature in the downcast shafts of deep mines in the presence of water flows into the shafts from the fixed space – compensation of air heating due to hydrostatic compression occurs as a result of the combined action of two processes: heat air exchange with wet wall of the shaft and convective heat transfer due to the separation of droplet moisture. The effect of moisture evaporation from the surface of the shaft wall is negligible.

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***Authors*: Artem V. Zaitsev,** *Doctor of Engineering Sciences, Head of the Sector, aerolog.artem@gmail.com, https://orcid.org/0000-0002-2314-0482* (*Mining Institute of the Ural branch of the Russian Academy of Sciences, Perm, Russia*), **Mikhail A. Semin,** *Candidate of Engineering Sciences, Researcher, seminma@outlook.com, https://orcid.org/0000-0001-5200-7931* (*Mining Institute of the Ural branch of the Russian Academy of Sciences, Perm, Russia*), **Oleg S. Parshakov,** *Junior Researcher, olegparshakov@gmail.com, https://orcid.org/0000-0001-5545-442X* (*Mining Institute of the Ural branch of the Russian Academy of Sciences, Perm, Russia*).

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