Study of the Convective Stratification of Airflows in a Mine Shaft

E V Kolesov, B P Kazakov and E L Grishin

Mining Institute of the Ural Branch of the Russian Academy of Sciences,
78a Sibirskaya St, Perm, Perm Krai 614007, Russian Federation

E-mail: kolesovev@gmail.com

Abstract. The experimental study of heat and mass transfer in the atmosphere of a skip shaft of a Gypsum mine was carried out during the summer and winter seasons. The air flow overturning was observed in the winter season due to the ingress of cold heavy air from the surface into the shaft space. To analyze this phenomenon, a computational fluid dynamics (CFD) model of heat and mass transfer processes in a mine shaft was developed, considering the vertical temperature gradient, roughness of the shaft walls, heat exchange with the shaft lining. Based on numerical simulation, it was found that at relatively low air velocities in the shaft and with a relatively large difference between warm air in the shaft and cold air on the surface, the latter begins to penetrate the shaft and descend down it, gradually filling its space. The interaction of cold air from the surface with the warm air rising up the shaft, as well as with warm walls of the shaft leads to the formation of an unsteady convective vortex cellular structure along the shaft. The depth of the vortex depends on the velocity of the air in the shaft, as well as the difference between the temperatures of the warm and cold air. Based on the obtained numerical simulation data, it was possible to calculate the minimum allowable air velocity at which partial return air flows appear in the shaft cross-section.

1. Introduction

In the context of an increase in the volume of minerals extracted by mining enterprises, the size of the development depth and area of new mine fields are increasing and mine ventilation networks are becoming more extended and fortified. Often air is supplied to a mine and returned to the surface through several mine shafts, which greatly complicates the ventilation process and makes it difficult to predict the airflows in each mine working. One of the significant reasons for this complication, especially in a cold climate, is the natural draft, which is the driving force of airflows in mines, along with the pressure generated by primary fans. Natural draft is caused by the difference in the weight of air columns in mine shafts due to the different air temperatures in them [1-3].

As a rule, the natural draft in mines can be investigated by calculating the average weight of air in each vertical or inclined shaft [4,5]. Classically, network calculations of air distribution are generated following Kirchhoff’s rules [6, 7], assuming that air moves as a whole, forward or backward, without other degrees of freedom. Therefore, this approach does not allow one to predict the dynamic effects of airflows in mine shafts associated with multidirectional air movement, convective stratification of flows caused by a low average flow rate, and large vertical temperature gradients that do not consider the influence of these effects on a natural draft. Multidirectional air movements in mine shafts can lead, under certain circumstances, to the uncontrolled overturning of the air stream, which, in turn, has significantly negative consequences to the safe operation of mines.

For example, in situ measurements of air distribution in the Knauf Gips Novomoskovsk mine during the winter found that at sufficiently low air temperatures at the surface, the outgoing air stream was overturned in the ventilation skip shafts. It was assumed that the rollover occurred when the flow rate of the warmer air emanating from the shaft was small and did not stop cold air from penetrating into the shaft mouth. The cold air interacted with the warm airflow rising from the main shaft. As a result of the...
gradual filling of the shaft with cold air, the hydrostatic weight of the air column increased, changing the amount of natural draft in the ventilation circuit of the mine. Further, the airflow rate in the shaft decreased even more, and at a certain moment, the airstream was overturned.

Bidirectional air movements in shafts during the winter were also detected during field studies at other mines such as in an Estonia shale mine and the Glubokaya mine in Norilsk during the construction of several shafts [8]. Cold air entering a mine shaft from the surface due to convective stratification or the airflow overturning can lead to a decrease in the air temperature to below +2°C, which is prohibited by the safety rules for mining and processing of solid minerals. This is primarily because at, air temperatures below +2°C, the cooling of the shaft lining occurs, which can cause critical temperature deformations of the tubing string, leakage, and destruction of the lining. Secondly, low air temperatures can negatively affect the health of miners.

It should be noted that according to mining safety rules the minimum allowable air velocity at a mine can be determined by the formula:

\[ V_{\text{min}} = \frac{0.1 P}{S} \text{ m/s}, \]

where \( S \) is the heading cross-sectional area, \( m^2 \); \( P \) is the working perimeter, \( m \).

In practice, this formula can also be used to calculate airflow rates not only in the workings of underground horizons, but also in vertical mine shafts, for example, during mine construction or renovations, or in the period before a mine reaches its design capacity or at the stage of its conservation. In these cases, the required amount of air per mine can be less than during design capacity, and the airspeed in one or more shafts can be decreased. Low air velocity is especially dangerous in air exhaust shafts because this can lead to an overturning of the air jet, which has been confirmed by other studies [8]. Therefore, it is necessary to develop a formula for calculating the permissible minimum air velocity in vertical shafts, ensuring the absence of a partial-return or fully returning airflows in the cross-section of a shaft when temperatures drop.

Existing research focused on aerodynamic processes in mine shafts, as a rule, describes theoretical, experimental, or numerical studies of aerodynamic drag in shafts due to wall roughness, or frontal and local resistance [9-11]. The first research study devoted to convective stratification in mine shafts is the work of Shalimov and Kazakov [2]. In a theoretical study using a two-dimensional formulation and the approximation of a laminar flow, a critical Rayleigh number was obtained in [2], which was determined from the longitudinal gradient of the average mass air temperature, the excess of which generated the development of an unsteady convection in a shaft (convective instability with respect to small perturbations of the flow parameters) during the main fan stoppage. In continuation of this research, an amendment was made to the critical Rayleigh number to take into account air heating due to hydrostatic compression along with the height of the shaft [13]. However, it should be noted that the air movement in mine shafts, even at very low velocities, occurs in a turbulent, not laminar, mode. Moreover, the problem of the airflow convective instability in a shaft concerning small perturbations, which has been sufficiently studied in the literature, differs from the problem of conditions associated with the occurrence of partial-return flows: the latter can form in a shaft earlier, be steady-state and stable in relation to small disturbances of the flow [14]. Studies of air flows partial return in mine shafts in conditions of temperature gradient are almost not presented in the literature. An exception is work [14] in which the partially return air flows in vertical mine shafts are studied in case when the temperature of the air rising in the vertical mine shaft is much higher than the temperature of the shaft walls.

In this article we continue the study [14]. However, this article describes the heat and mass transfer in mine shaft in a slightly different formulation of the problem: instead of cooling the air flow by the shaft walls, the inflow of cold air from the atmosphere into the shaft is considered. This study aims to determine the minimum allowable velocity of the air in a shaft, excluding the possibility of partial return flows manifesting, depending on the temperature difference between the outgoing and atmospheric airflows. The research methodology includes the formulation of a mathematical model of air movement along a shaft in a turbulent flow regime and conducts numerical multivariable modeling.
2. Experimental research in a gypsum mine

As a result of an experimental study in the Knauf Gips Novomoskovsk mine (figure 1), the aerodynamic and thermophysical parameters of the airflows in the ventilation skip shafts No. 1, 2 and 3 were calculated and it was found that with sufficiently low air temperatures at the surface that the airflow in the shafts would overturn. Thus, experimental evidence of unstable ventilation in mine shafts during the winter has been obtained.

![Figure 1. Simplified Knauf Gips Novomoskovsk mine ventilation network](image)

A forced ventilation method is used in this mine. During the summer, fresh air only enters the underground level of the mine through the cage shaft in the amount of 8000 m³/min, and the exhaust air, with a temperature of about +12°C, leaves the mine through service ventilation shaft No. 3 (7000 m³/min), and through ventilation skip shafts No. 1 (300 m³/min) and No. 2 (700 m³/min), although the latter has limited airflows since the diameter is only 5 m. The mine level is located at a depth of 120-140 m relative to the earth's surface. During the winter, depending on the air temperature at the surface of the mine, an overturning of the airflow in skip shaft No. 1 was observed due to an ingress of cold heavy air into it along with a decrease in the natural draft, which led to the freezing of the shaft lining.

To eliminate freezing of skip shaft No. 1, the bulkhead on the ventilation drift leading to the skip shaft No. 1 was removed. As a result of this action, the airflow rate on the skip shaft No. 1 slowed to approximately 800 m³/min. Then an increase in air consumption in skip shaft No. 1 occurred due to a decrease in skip shaft No. 2. At the same time, at skip shaft No. 2 due to low atmospheric temperatures, the airflow rate also began to overturn, leading to the freezing of that lining.

At the first stage of the study, a mine ventilation network model developed a one-dimensional formulation based on Kirchhoff’s first and second rules in the AeroSet ventilation software (https://aeroset.net/). In this case, an air distribution model of the time when the overturning of the airflow rate in one of the skip shafts occurred can be analyzed. Figure 2 shows the results of modeling the airflow rates distribution in the ventilation network, taking into account the effect of a natural draft and the effect of a heat exchange with the shaft walls. It was assumed that the atmospheric air temperature was –20°C, the temperature of the air entering the ventilation channel of the shaft from the heater was +2°C, and the rock wall temperature was +12°C.

Case A corresponds to the proposed model when the airflow in skip shaft No. 1 has overturned. The negative air temperature set at the initial moment of time remains in the shaft throughout the entire time...
of the calculations until the stationary ventilation mode is established with an overturned airstream. Case B corresponds to the situation when the airflow in skip shaft No. 2 has overturned. In this case, in correlation with Case A, at the initial moment of time, a negative air temperature is set in skip shaft No. 2. The result is a calculated air distribution for a steady-state ventilation mode with an overturned airstream.

It should be noted that if, at the initial time the air temperature in skip shaft No. 2 is set equal to the wall temperature of the rock mass (+12°C), then the result is a calculated air distribution for the steady-state ventilation mode, where the airflow in skip shaft No. 2 is not overturned (Case C). Thus, the resulting air and heat distribution in the mine ventilation network is dependent on the initial conditions.

![Figure 2. The steady temperature and air flow rates distributions in the Knauf Gips Novomoskovsk mine ventilation network following different initial calculation parameters](image)

It was not possible to explain this phenomenon with a mathematical model of a mine ventilation network using a one-dimensional setting based on Kirchhoff’s first and second rules. It is assumed that the overturning mechanism of the airflow in skip shafts No. 1 and No. 2 has a convective nature. The proposed qualitative explanation of this phenomenon is as follows. When the flow rate of the air emanating from a shaft is small than in the shaft cross-section under the influence of the temperature difference, partially returned airflows are formed from the atmosphere through the mine building into the shaft mouth, cold air streams begin to penetrate the shaft. Cold streams descend along the shaft, interacting with the warm airflow rising from the mine, cooling it due to convective mixing. As a result of the gradual filling of the shaft with cold air, the hydrostatic weight of the air column increases, the mine natural draft changes, and the airflow in the shaft decreases even more and as a result, it overturns at a certain moment. To study the conditions for the emergence and development of convective stratification of air in mine shafts and its quantitative description, CFD was required.

### 3. Physical model of air movement in a mine shaft

The movement of air and gas flows in mine shafts proceeds in a turbulent manner even at low airflow velocities at the order of $10^{-1}$ m/s. Following turbulent flows velocity, pressure and temperature fields and other physical quantities develop a complex vortex irregular structure.

To determine the air velocity and temperature fields in the shaft the Reynolds-averaged mass, momentum, and energy conservation equations were used.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0, \quad (1)
\]

\[
\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \nabla \cdot (\mu \nabla \vec{V}) - \nabla \cdot \vec{R}, \quad (2)
\]

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \vec{V} E) = -\nabla \cdot (p \vec{V}) + \nabla \cdot (\lambda \nabla T) - \nabla \cdot \left( \vec{R} \cdot \vec{V} \right), \quad (3)
\]
where \( \rho \) is the air density, \( \text{kg/m}^3 \); \( \overrightarrow{V} \) is the vector of the Reynolds-averaged air velocity, \( \text{m/s} \); \( p \) is the hydrostatic pressure, \( \text{Pa} \); \( \mu \) is the dynamic viscosity of air, \( \text{Pa} \cdot \text{s} \); \( R \) is the Reynolds turbulent stress tensor, \( \text{Pa} \); \( E \) is the specific total energy of air, \( \text{J/kg} \); \( \lambda \) is the heat conductivity of the air, \( \text{W/(m} \cdot \text{K}) \).

The Reynolds-averaged equations system is not closed, since its solution requires additional six equations for the components of the symmetric turbulent stresses tensor \( R \). To solve the closure problem, a physically substantiated mathematical model is required that allows turbulent stresses to be calculated. This goal is achieved using one or more turbulence models.

In this work the Shear Stress Transport (SST) \( k-\omega \) low-Reynolds turbulence model was used. It combines the advantages of the \( k-\omega \) and \( k-\varepsilon \) models and, at the same time, is free from their drawbacks. The SST \( k-\omega \) model is a superposition of the \( k-\omega \) and \( k-\varepsilon \) models, designed in such a way that the equations of the \( k-\varepsilon \) model are used to calculate the flow in a free flow, and the equations of the \( k-\omega \) model are used in the region near the walls, which gives a more accurate solution in the boundary layer [15].

In the Ansys SpaceClaim module, a simplified three-dimensional model of a vertical shaft with a diameter of 5m and a height of 130m was built. The following initial and boundary conditions were used to generate a computational model of the shaft. The air temperature in the shaft was set to +12°C to start. The temperature of the air outgoing from the mine was also defined as +12°C, which corresponds to the temperature of the rocks at the depth of the working horizon. The first-type boundary condition was set for the temperature of the shaft walls considering the geothermal gradient, a no-slip condition was set for the velocity, and the condition of zero static pressure was set at the exit in the computational domain. A region of the atmosphere with a constant temperature was modeled above the shaft (figure 3). The variable parameters of the model were the mine shaft diameter, the airflow velocity outgoing from the mine, and the atmospheric air temperature.

Several finite-volume meshes with different numbers of elements were built to analyze the mesh independence. As a result, a mesh consisting of 2.9 million tetrahedral elements and 1.1 million nodes was selected, with a prismatic boundary layer of solid walls and the parameter \( Y+ \) not exceeding 1 (figure 3).

To determine the velocity and pressure distribution, the algorithm for numerical calculation of the semi-implicit pressure linked equations (SIMPLE) was used. The second order of spatial sampling accuracy was also used. To speed up the calculations, the computations were parallelized between eight cores of the central processor using the MPI Local Parallel platform.

**Figure 3.** A) a general view of the computational domain (mine shaft); B) the median longitudinal section of the computational domain section, divided into finite elements

### 4. Results and discussions

A series of calculations were carried out using different air velocities outgoing from the mine, as well as with different air temperatures at the surface. The calculation results analysis was carried out in terms of the dimensionless Reynolds (Re) and Rayleigh (Ra) numbers:
\[ Re = \frac{V_0d}{\nu} \]  
\[ Ra = \frac{g\beta(T_0 - T_A)d^3}{\nu \chi} \]

where \( V_0 \) is the mean velocity of the airflow outgoing from the mine, m/s; \( d \) is the shaft diameter, m; \( \nu \) is the air kinematic viscosity, m\(^2\)/s; \( g \) is the gravity acceleration, m/s\(^2\); \( \beta \) is the air volumetric expansion coefficient, 1/\(^\circ\)C; \( T_0 \) is the temperature of the airflow outgoing from the mine, \(^\circ\)C; \( T_A \) is the air temperature on the surface, \(^\circ\)C; \( \chi \) is the air thermal diffusivity, m\(^2\)/s.

The Reynolds number is essentially a measure of the ratio of the inertial forces acting in the flow to the viscosity forces that prevent the acceleration of the fluid, whereas the Rayleigh number characterizes the magnitude of the effect of thermogravitational forces caused by the temperature difference \( T_0 - T_A \).

The boundary of free convection influence on the shaft ventilation was determined to be caused by the temperature drop, due to convective flows of cold air descending into the shaft from the surface. Figure 4 shows the limiting curve in Re-Ra coordinates. In the area below the limiting curve, the air flow in the shaft is stable and unidirectional; above the curve the air movement in the upper part of the shaft is bidirectional and potentially unstable.

For each value of the temperature difference, the corresponding Rayleigh number can be determined by formula (5), for which, in turn, the limiting value of the Reynolds number is determined, at which return air flows begin to appear at the shaft mouth. The critical velocity can be calculated using formula (4), below which there is a violation of the flow homogeneity in the shaft cross-section and the formation of return convective vortices.

The calculations showed, that when the air flow velocity is below the critical one, the cold air streams penetrate the shaft from the surface and mix with the main stream form a periodic variable in time cellular structure in the shaft. The number of cells and the depth of the resulting vortex structure depends on the temperature drop out of the mine and the atmospheric air, as well as on the mean air velocity. The greater the temperature difference and the lower the velocity of the main flow, the deeper the penetration of the return vortices from the surface. As an example, air velocity vector field and air temperature field in the upper part of the shaft are shown in the case when the air flow velocity is below the critical one (fig. 5).
Figure 5. The air velocity vector field and air temperature field in the upper part of the shaft in the case when the air flow velocity is below the critical one.

The limiting curve shown in figure 4, reflects the following pattern: the effect of thermogravitational forces is stronger and inertial forces are less. Thus, forced convection has a stabilizing effect on the air flow profile. However, if the Rayleigh numbers are large enough, then the effect of free convection will be significant even at increased Reynolds numbers. For the Knauf Gips Novomoskovskmine case, the critical velocity was 0.4 m/s with a temperature difference of $T_0 - T_A = 32 \, ^\circ C$.

The numerical dependence of the dimensionless critical airflow velocity on the dimensionless temperature decrease, shown in figure 4 describes the following linear approximation:

$$Re_{cr} = 2.2 \cdot 10^{-7} \cdot Ra.$$  \hspace{1cm} (6)

Using formula (6), the values of the critical and minimal air velocities in shafts which ensure the absence of return air flows caused by the temperature difference can be calculated as follows:

$$V_{min} = kV_{cr} = k \frac{Re_{cr} \nu}{d} = \frac{k \nu}{d} \left( \frac{2.3 \cdot 10^{-7} g \beta (T_0 - T_A) d^3}{\chi} \right).$$  \hspace{1cm} (7)

where $k$ is the assurance coefficient.

This formula can be used to design ventilation systems for mines and to calculate the required air velocity for ventilating upcast mine shafts under conditions where there is a significant difference between the air temperature leaving the mine and the ambient air.

Conclusions

As a result of the experimental study of the aerodynamic and thermophysical parameters of the air in the skip shafts of the Knauf Gips Novomoskovsk mine during the cold season, depending on the air temperature on the mine surface, the air flow overturning was noticed due to the ingress of cold heavy air from the surface into the shaft space. To analyze this phenomenon, multi-parameter three-dimensional numerical simulations of the aerodynamic and thermodynamic processes in a mine shaft were carried out in the Ansys Fluent software, taking into account the vertical temperature gradient, the roughness of the shaft walls and heat transfer with the shaft lining. It was found that the interaction of cold air from the surface with warm outgoing air, as well as with warm shaft walls, leads to the emergence of an unsteady convective vortex cellular structure along the shaft. The depth of the vortex depends on the velocity of the air in the shaft, as well as the difference between the temperatures of the warm and cold air. Based on the obtained numerical simulation data, it was possible to calculate the minimum allowable air velocity at which partial return air flows appear in the shaft cross-section. The
results can be used to design ventilation systems for mines and to calculate the required air velocity for ventilating upcast mine shafts under conditions where there is a significant difference between the air temperature leaving the mine and the ambient air.

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