NUMERICAL ANALYSIS OF INFLUENCE OF EXOGENOUS FIRE IN DOG HEADING ON PARAMETERS OF THE AIR STREAM FLOWING THROUGH THIS HEADING

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Abstract:
Flow of ventilation air stream through the dog heading with a fire centre is the flow with complex character, during which as a result of emission of fire gases into the mining atmosphere, there occur to disturbances of its flow. In the paper there is presented a numerical analysis of an influence of exogenous fire in a dog heading, on the parameters of the ventilation air stream flowing through this heading. Modeling tests were carried out with a use of ANSYS software, basing on the Finite Volume Method. For the made assumptions, there were determined physical parameters of air stream flowing through the heading with a fire centre, and also changes in mass fraction of gases in this stream during its flow through the analyzed heading: oxygen, carbon monoxide and carbon dioxide. As a result of performed analysis over the fire centre, the local increase of velocity and temperature and violent decrease of static pressure were recorded. Model of heading presented in the paper gives possibilities for development, and then the analysis of more complicated problems in a range of ventilation of mining headings.

Key words: CFD, underground fire, belt conveyor fire, airflow

INTRODUCTION

One of the fundamental hazards occurring in the hard coal-mining is fire risk. It is confirmed by the number of registered fires in recently years in underground mining headings. In years 2000-2013, there was totally 91 fires in the hard coal mining, which 70 were spontaneous fire (caused by combustion of coal), and 21 – exogenous fires (caused as a result of ignition of combustible material e.g. wood, oil, conveyors belt, electric cables etc.). In years 1989-2007, there were fifteen inflammations of conveyor belt resulting in death of three workers of hard coal mines [12].

According to the definition in regulation of the Ministry of Economy regarding to the occupational safety and health, traffic management and specialized fire protection in underground mining plants [7], underground fire should be understand as a presence of the open fire in underground heading *i.e.* glowing or burning with open flame substance, as well as persistence of mining smoke in the air or persistence of carbon monoxide in the current flow of air in concentration greater than 0,0026%. The condition concerning the carbon monoxide concentration does not include the cases, where such its concentration is connected with using permitted manufacturing processes in mining headings.

Endogenous and exogenous fires are large hazard for working crew in mining headings and cause economic losses for mining plants. Particularly dangerous are exogenous fires, which are developing very fast. In a case of endogenous fires, their incubation time is much longer, what creates a possibility to take preventive actions, not permitting to its formation, and subsequently to the development [2].

Occurrence of fire in underground mining heading disturbs the process of its proper ventilation [4, 5]. The ventilation air stream becomes in this case the source of oxygen supporting the flame and the carrier of smoke and gases being moved to the subsequent mining headings [11].

Carrying out the studies connected with airflow through the heading during a fire under *in situ* conditions is difficult and expensive. In order to test the phenomena presented during the fire it is necessary to use another methods enabling their analysis.

Such possibilities create modeling studies of flows, based on the numerical simulations. In recently years, these methods are more often used for solving problems associated to process of ventilation of mining headings [3, 6, 9, 10, 11].

In the paper there are presented results of numerical analysis of air flowing through the dog headings during the fire of conveyor's belt.

The main aim of the tests was to determine velocity fields, pressure and temperature of air in analyzed heading. Developed model enabled also to determine the changes in oxygen concentration in airflow, as well as carbon monoxide and carbon dioxide discharged during the fire into the atmosphere of a heading.

Analysis was performed using the Finite Volume Method. Developed model of airflow through the heading, in which a fire occurred, gives a lot of opportunities for development and simulations of more complicated problems connecting with processes of airflow through the mining headings.

MATHEMATICAL MODEL OF FLOW

Computational Fluid Dynamics (CFD) is a simulation method of phenomena connected with flow of liquid and gases, heat and mass transfer, and also chemical reactions [8].

Software based on CFD enables to determine the physical parameters of airflow or fluid flow (distribution of velocity field, distribution of pressure field), heat transfer (temperature field), as well as the physical-chemical changes.

For modeling of an issue of air flowing through the mining dog heading, in which fire of conveyor's belt took place, ANSYS software was used. Problems connecting with fluid transport in this software are solved basing on following fluid mechanics and thermodynamic equations [1]:

– The Mass Conservation Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \overrightarrow{v}) = S_m \qquad (1)$$

where:

$\overrightarrow{v}$ - velocity, m/s
ρ - density, kg/m^3
t - time, s
S_m - the mass added to the continuous phase from the dispersed second phase, kg/s

– The Momentum Conservation Equations

$$\frac{\partial}{\partial t}(\rho \overrightarrow{v}) + \nabla \cdot (\overrightarrow{v}\,\overrightarrow{v}) = -\nabla p + \nabla \cdot (\overline{\tau}) + \rho \overrightarrow{g} + \overrightarrow{F} \qquad (2)$$

where:

P - static pressure, Pa
$\overline{\tau}$ - the stress tensor, Pa
$\overrightarrow{g}$ - the gravitational body force, m/s^2
$\overrightarrow{F}$ - the external body force, N

– The Energy Equation

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\overrightarrow{v}(\rho E)) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \overrightarrow{J}_j + (\overline{\tau}_{eff} \cdot \overrightarrow{v}) \right) + S_h \qquad (3)$$

where:

E - total energy, J/kg
k_{eff} - the effective conductivity, W/(mK)
T - temperature, $^\circ$K
$\overrightarrow{J}_i$ - the diffusion flux of species, kg/(m^{2}s)
S_h - the heat of chemical reaction, W/m^3

For the analysis there was used the „k-ε" turbulence model belonging to semi-empirical models, characterizing by parameters determined basing on experimental tests. This model describes components of Reynolds turbulent stress tensor according to Boussinesq hypothesis [8]. According to this hypothesis, turbulent stresses are proportional to the velocity of deformation and are expressed using the dynamic viscosity coefficient of turbulence μ_t. In the equation for components of stress tensor, k and ε values occur. In order to their determination there is necessary to introduce two additional transport equations in a form [1]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (4)$$

and

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon -$$

$$- \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \qquad (5)$$

where

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right] \qquad \eta = S \frac{k}{\varepsilon} \qquad S = \sqrt{2 S_{ij} S_{ij}}$$

where:
μ_t - the turbulent viscosity, Pa·s
k - the vkinetic energy of turbulences, m^2·s^{-2}
ε - kinetic energy dissipation speed of turbulences, m^2·s^{-3}

Applied software enables also modeling of phenomena, in which mixing and transport of chemical substances (*e.g.* emitting gases during the fire) take place, by solving the equations describing source of convection, diffusion and chemical reactions for each of the element. In order to perform this analysis, „*species transport*" model was applied, in which there were taken into account additional parameters, such as: mass fraction of *i-th* component of mixture and rate of its formation [1].

DISCRETE MODEL OF FLOW

In order to perform an analysis, there was developed geometrical model of heading with a part of conveyor (Fig. 1a), which was submitted to discretization process (Fig. 1b).
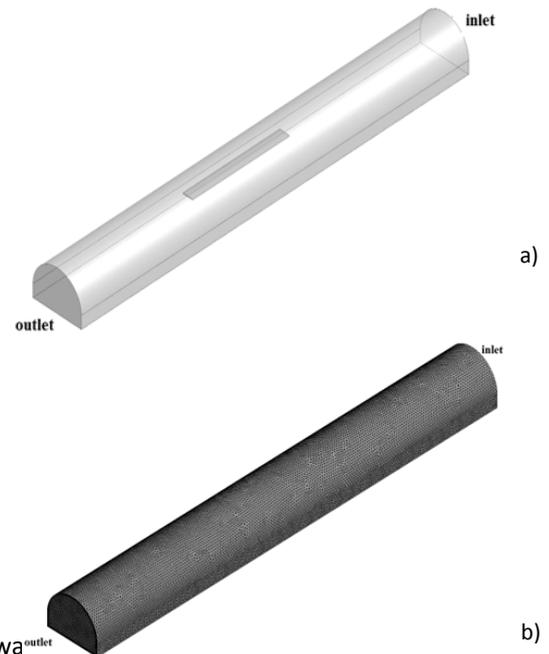

Fig. 1 Models of mining headings:
(a) and discrete model, (b) of mining heading with a part of conveyor

amounts to 40 m, its cross-section 5 m^2, whereas surface of conveyor, being source of fire equals to 10 m^2.

In the discretization process, concentration of the mesh in the region of the boundary layer and in the part of conveyor model was performed. It is assumed, that air is an incompressible fluid with a temperature at the inlet amounting to 293.0°K.

As an inlet boundary condition there was assumed constant velocity field of air stream, constant values of kinetic energy of turbulence, and its rate of dissipation, which was determined assuming 5-percentage of turbulence intensity at the inlet.

In the inlet cross-section of analyzed heading, the uniform velocity field with a value of 2.0 m/s was assumed. For analyzed model outlet boundary condition was defined, whereas walls were defined as impermeable, which surface roughness corresponded to the height of 0.2 m. Calculations were performed for the pressure, which reference value amounted to 101325 Pa.

In modeling of fire there was assumed that heat source (conveyor's belt) releases to surrounding mass stream of gases, containing products formed in combustion. As combustible material, there was selected rubber with the following parameters: density 1200 kg/m^3, specific heat 1.4 kJ/kgK, and heat conductivity 0.17 W/mK.

It was also assumed that at the inlet of heading the oxygen mass fraction of the air amounts to 21%, whereas gases, emitted to the atmosphere in a result of fire, are carbon monoxide and carbon dioxide. Ignition temperature of conveyor's belt was set to 1200°K.

So developed model, was subjected to the numerical analysis.

THE TESTS RESULTS

Based on performed calculations, distributions of changes of velocity field, temperature and pressure of air stream flowing through the dog heading with a fire centre were determined.

Also changes in oxygen concentration in the air stream, carbon monoxide and carbon dioxide emitted from the source of the fire into the atmosphere of a heading were determined. Determined physical parameters of air stream and mass fractions of particular gases in heading with fire centre were compared with their appropriate values obtained during the airflow through the heading without the fire.

In a Figure 2b, there is presented distributions of air stream velocity flowing through the dog heading during the fire of conveyor's belt, and in a Figure 2a characteristic of velocity of this stream along headings with and without the fire centre.

From performed analysis results that the local increase of velocity of air stream occurs in the zone over the fire centre. It is connected with emitted mass stream of gases into the atmosphere during the fire, which causes local disturbance of the airflow.

Ventilation air stream is pull inside the convection stream above the fire centre, and subsequently as a result of convection it is displaced towards the roof of heading. This stream reaches the maximum value of the velocity, equal to 12.6 m/s, in the half length of the conveyor's belt.

In a case of airflow through the dog heading without the fire centre, value of velocity is subjected to small decrease (up to 1.83 m/s at the outlet) due to the occurrence of local drags.

In a Figure 3. distribution of static pressure of air stream flowing along the dog heading with fire centre and without the fire centre is presented.

Analyzing obtained characteristics, one can conclude that rapid decrease of static pressure occurs in a fire zone, forming negative pressure zone. In a case of airflow through the heading without fire centre, one can observe a small, linear decrease of static pressure along its length.
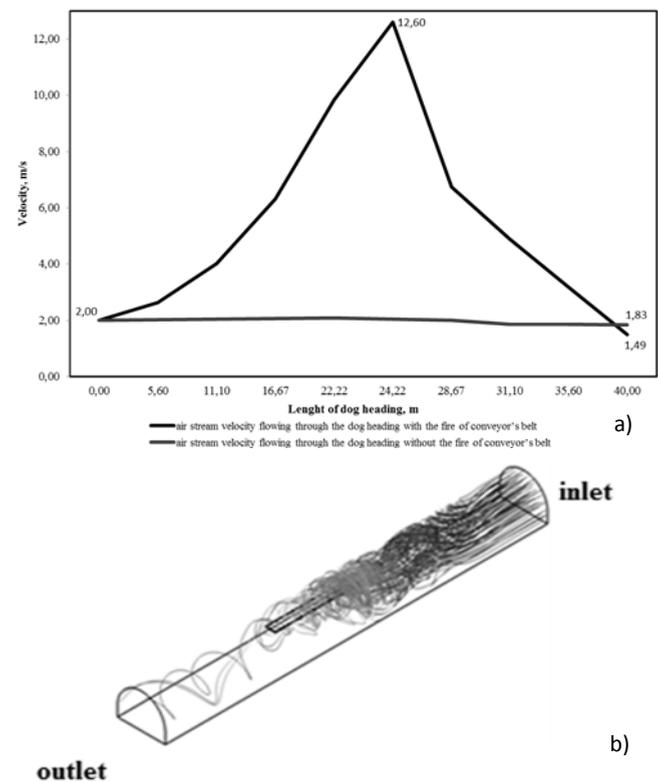

Fig. 2 Velocity characteristics:
(a) and the trajectory of particles of air flowing through the dog heading during the fire of conveyor's belt (b)
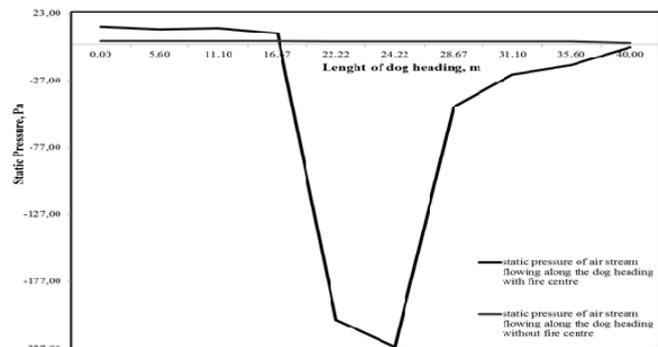

Fig. 3 Static pressure characteristics of air stream flowing along the dog heading with fire centre and without the fire centre

Temperature characteristics are presented in a Figure 4a, and temperature distribution along the analyzed heading is presented in a Figure 4b.

Performed analysis indicated that rapid increase of temperature occurs in the section of heading with burning conveyor's belt. As a result of emission of heat into the atmosphere at the outlet from heading, temperature of the air stream amounted to ca. 316°K, what means its increase of more than 20°K. In a result of fire, temperature over conveyor increases to 1050°K. In a case of airflow through the heading without the fire centre, its temperature at the inlet increases to ca. 0.5^{o}K.

In Figures 5a, 6a and 7a there are presented characteristics of mass fractions of oxygen, carbon monoxide and carbon dioxide in dog heading with the fire centre. In Figures 5b, 6b and 7b obtained distributions of mass fraction of these gases are presented in graphical form.

In the analyzed model, at the inlet of heading there was assumed zero concentrations of carbon monoxide and carbon dioxide in the air stream. As a result of the emission of these gases into the atmosphere during the fire, their con-

centrations at the outlet amounted to 0.7% and 2%, for carbon monoxide and for carbon dioxide respectively.

Concentration of oxygen in the airflow through the analyzed heading with fire centre decreased from 21% to 14.3%.

In a case of airflow through heading without the fire centre, mass fraction of oxygen, carbon monoxide and carbon dioxide did not change (Fig. 5a, 6a, 7a).

Based on the performed analysis, there was determined

also a smoke zone of dog heading as a result of existing fire of conveyor's belt (Fig. 8).

This zone includes region over the fire centre, whereas flow of smoke takes place mainly under the roof of heading, and its direction is compatible with the direction of airflow. For assumed velocity of ventilation air stream at the inlet amounted to 2 m/s, there has been no backflow fire smokes.
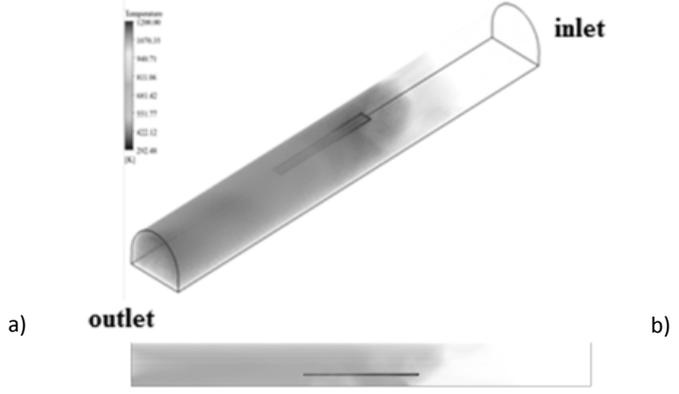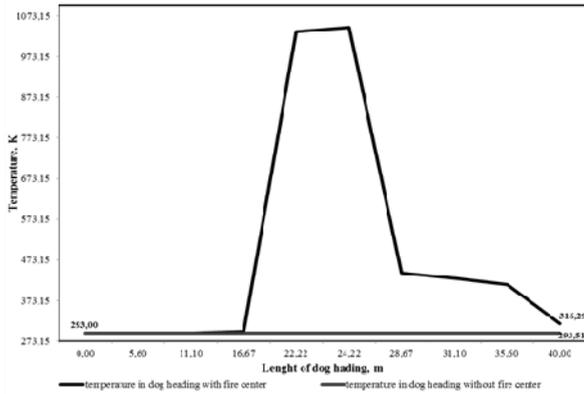

Fig. 4 Temperature characteristics (a) and temperature distribution (b) in dog heading with fire centre
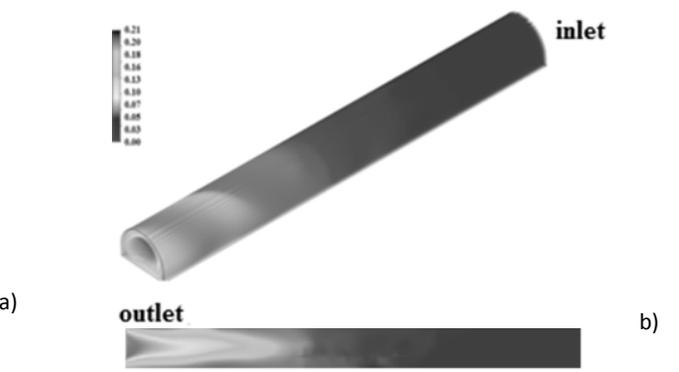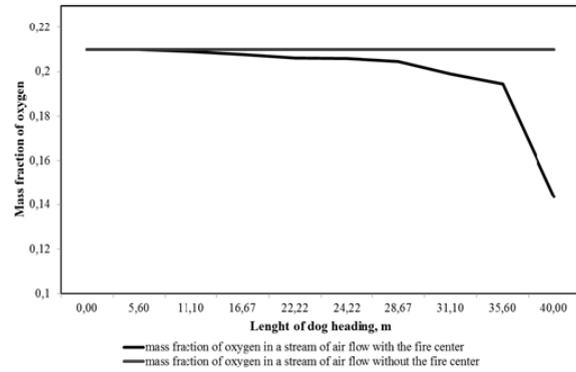

Fig. 5 Mass fraction of oxygen characteristics (a) and oxygen distribution (b) in dog heading with fire centre
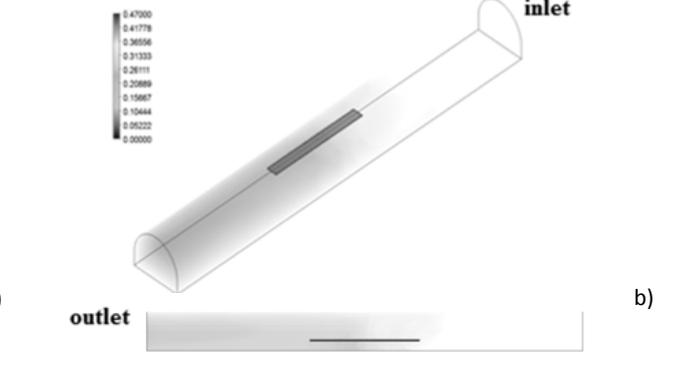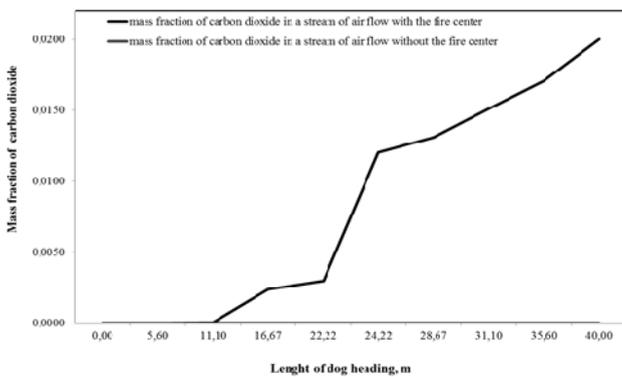

Fig. 6 Mass fraction of carbon dioxide characteristics (a) and carbon dioxide distribution (b) in dog heading with fire centre
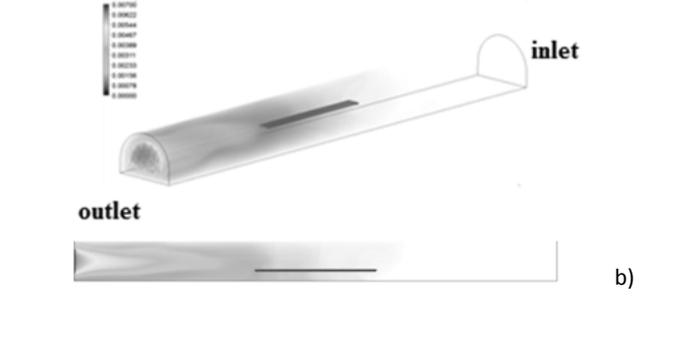

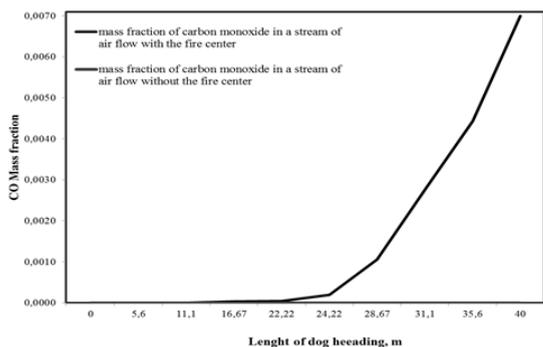Fig. 7 Mass fraction of carbon monoxide characteristics (a) and carbon monoxide distribution (b) in dog heading with fire centre
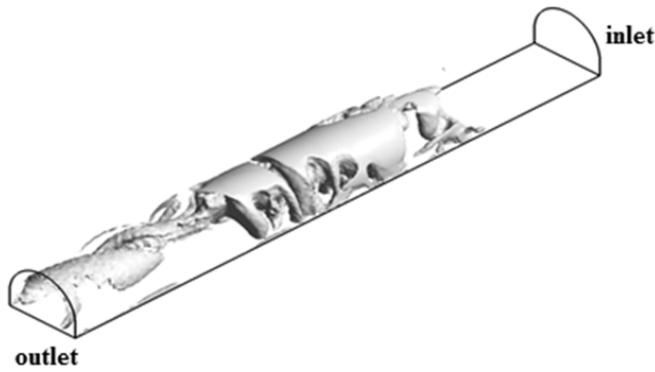
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Fig. 8 Smoke zone in dog heading with fire centre

CONCLUSIONS

Model used for analysis of ventilation air stream flow through the mining heading with fire centre enabled to determine the velocity fields, pressure and temperature of flowing air stream.

As a result of performed simulation, also changes in the concentrations of oxygen, carbon monoxide and carbon dioxide in the ventilation air stream were determined. Three-dimensional analysis of this flow indicated that occurrence of fire in mining heading causes its significant disturbance.

During the airflow through the fire zone, local very rapid changes of its physical parameters occur. In the analyzed case, there was recorded local increase of velocity and temperature and rapid static pressure drop over the fire centre.

In the air stream flowing through the fire centre, great mass changes of its components, were observed. As a result of emission of fire gases into the atmosphere, a significant decrease of oxygen concentration in the air and large increase of carbon monoxide and carbon dioxide were recorded.

Based on the analysis carried out, one can conclude that application of CFD to analysis of airflow through the mining headings with fire centre can be an alternative, relating to the underground tests.

Direct measurements of physical parameters of air stream in mining headings during fire, require application of specialized and expensive equipment and can be very dangerous for persons performing them.

It should be emphasized that developed model and applied software give a lot of possibilities for more complicated analysis of problems in a scope of ventilation process of mining headings.

Obtained results should be regarded as preliminary, and the developed model, as a base for further analysis of airflow through the mining headings.

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