APPLICATION OF MODEL-BASED TESTS FOR ANALYSING THE CONSEQUENCES OF MINE FIRES

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Abstract: One of the most common and most dangerous hazards in underground coal mines is fire hazard. Mine fires can be exogenous or endogenous in nature. In the case of the former, a particular hazard is posed by methane fires that occur in dog headings and longwalls. Endogenous and exogenous fires are large hazard for working crew in mining headings and cause economics losses for mining plants. Mine fires result in emission of harmful chemical products and have a crucial impact on the physical parameters of the airflow. The subject of the article concerns the analysis of the consequences of methane fires in dog headings. These consequences were identified by means of model-based tests. For this purpose, a model was developed and boundary conditions were adopted to reflect the actual layout of the headings and the condition of the atmosphere in the area under analysis. The objective of the test was to determine the effects of methane fires on the chemical composition of the atmosphere and the physical parameters of the gas mixture generated in the process. The results obtained clearly indicate that fires have a significant impact on the above-mentioned values. The paper presents the distributions for the physical parameters of the resulting gas mixture and the concentration of fire gases. Moreover, it shows the distributions of temperature and oxygen concentration levels in the headings under analysis. The methodology developed for the application of model-based tests to analyse fire events in mine headings represents a new approach to the problem of investigating the consequences of such fires. It is also suitable for variant analyses of the processes related to the ventilation of underground mine workings as well as for analyses of emergency states. Model-based tests should support the assessment of the methane hazard levels and, subsequently, lead to an improvement of work safety in mines.

Keywords: mine fires, methane combustion, numerical analysis.

1. INTRODUCTION

Underground coal exploitation is dangerous due to many natural and technological hazards (Brodny and Tutak, 2016a; Brodny and Tutak, 2016b; Brodny and Tutak, 2016c; Brodny and Tutak, 2018a; Brodny and Tutak, 2018b; Korban, 2015; WUG, 2017). One of the most common and most dangerous hazards is fire hazard. It is confirmed by the number of registered fires in recently years. In underground mining headings. In years 2008-2017, there was totally 79 fires in the hard coal mining, which 58 were spontaneous fire (caused by combustion of coal), and 21-exogenous fires (WUG, 2008-2017). Another dangerous event related to the risk of fire includes methane combustion. In the years 2008-2017, there were 25 such events in longwall areas and mined longwall faces of dog headings (WUG, 2008-2017). Some of these combustions led to the emergence of an advanced exogenous fire. Due to the fact that the methane hazard, which may be caused by combustion and/or explosion of methane when mixed with air, is one of the most serious hazards in mining, it is essential to analyse the effects of such events. This is particularly important with regard to mine ventilation systems. As a result of methane combustion leading to exogenous fires in mine headings, there is a series of chemical reactions which cause the emission of harmful and poisonous

gases of high temperature (the temperature of methane combustion in mixture with air is approx. 1,875°C, with methane content of approx. 10%) into the mine atmosphere.
Combustion of methane is a multiple step reaction summarized as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1}$$

More detailed analysis of the reaction mechanism shows that combustion of methane can actually produce combinations of CO or CO_2:

$$CH_4 + 2O_2 \rightarrow CO + 2H_2O \tag{2}$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{3}$$

$$2H_2 + O_2 \rightarrow 2H_2O \tag{4}$$

It thus transpires that these processes result in the generation of gasses, such as carbon monoxide (poisonous) and carbon dioxide (suffocating).
Occurrence of fire in underground mining heading disturbs he process of its proper ventilation. 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. Such an occurrence is also responsible for a change in the physical parameters of the air stream, thereby disturbing its flow through mining headings. In order to examine such phenomena, especially in terms of their impact on the flow parameters of the resulting gas mixture, it is necessary to implement relevant methods that allow for such an analysis. The combustion process is accompanied by a dynamic exchange of mass and energy in the reaction zone, whose course is determined by simultaneously occurring chemical, thermal and flow phenomena. Fires are thus extremely complex and elude clear definition. Taking into consideration the remarks above, it was assumed that the analysis of the impact of methane combustion in the mined heading face on the parameters of the air stream flowing through this heading would be conducted by means of model-based tests.
The objective of the test was to determine the effects of methane combustion on the chemical composition of the atmosphere and the physical parameters of the gas mixture generated in the process. The paper presents the distributions for the physical parameters of the resulting gas mixture and the concentration of fire gases. Moreover, it shows the distributions of temperature and oxygen concentration levels in the headings under analysis.
The methodology developed and presented in the paper, involving the use of model based tests, with account being taken of the actual measurement results, and used for analysing fire events should support the process of diagnosing and forecasting the consequences of these events in coal mining.

2. MATHEMAICAL MODEL

2.1. Governing equations

System of balance equations of mass, momentum and energy (equations of fluid handling) of one-component flow takes the following form (Sobieski, 2011):

$$\frac{\partial}{\partial t}(\rho) + div\left(\rho \vec{v}\right) = 0 \tag{5}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + div\left(\rho \vec{v}\vec{v}\right) = div\left(-p\overset{\leftrightarrow}{I} + \overset{\leftrightarrow m}{\tau} + \overset{\leftrightarrow t}{\tau}\right) + \rho \vec{s}_p \tag{6}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + div\left(\rho e \vec{v}\right) = div\left[\left(-p\overset{\leftrightarrow}{I} + \overset{\leftrightarrow m}{\tau} + \overset{\leftrightarrow t}{\tau}\right)\vec{v} + \overset{\rightarrow m}{q_s} + \overset{\rightarrow t}{q_s}\right] + \rho s_e \tag{7}$$

System of equations (5-7) in a vector form can be written as (Sobieski, 2011):

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho \\ \rho\vec{v} \\ \rho e\end{pmatrix} + div\begin{pmatrix}\rho\vec{v} \\ \rho\vec{v}\vec{v} + p\overleftrightarrow{I} \\ \rho e\vec{v} + p\overleftrightarrow{I}\vec{v}\end{pmatrix} = div\begin{pmatrix}0 \\ \overleftrightarrow{\tau}^{m} + \overleftrightarrow{\tau}^{t} \\ \left(\overleftrightarrow{\tau}^{m} + \overleftrightarrow{\tau}^{t}\right)\vec{v} + \vec{q}_s^{\,m} + \vec{q}^{\,t}\end{pmatrix} + \begin{pmatrix}0 \\ \rho\vec{s}_p \\ \rho s_e\end{pmatrix} \tag{8}$$

Variables presented in the system of equation (5-7) are (Sobieski, 2011):

$$\left\{\rho, \vec{v}, p, \overleftrightarrow{\tau}^{m}, \overleftrightarrow{\tau}^{t}, \vec{s}_p, e, s_e, \vec{q}_s^{\,m}, \vec{q}_s^{\,t}\right\} \tag{9}$$

where: p is the static pressure (Pa), V_x, V_y and V_z are the air velocity (m/s), C_1 is the factor of viscous resistance (1/m^2), C_2 is the factor of inertial resistance [1/m], ρ is the fluid density [kg/m^3].

2.2. Eddy dissapation model

The Eddy Dissapation Model was introduced by Magnussen (Magnussen and Hjertager, 1976) and its usage has become widespread in industrial applications. The combustion model is based on the following single-step reaction:

$$fuel + r_j oxider \leftrightarrow (1 + r_j)products \tag{10}$$

The Eddy Dissipation Model was based on three assumptions (Wang, 2016):

1. combustion reaction rate is infinitely fast;
2. the fuel consumption rate in turbulent diffusion flames is solely determined by the turbulent mixing rate of fuel and oxidizer; 3
3. the fuel consumption rate is proportional inversely to the turbulent time scale (turbulent kinetic energy divided by turbulent dissipation rate).

According to these assumptions, Magnussen and Hjertager gave the following fuel reaction rate expression (Wang, 2016):

$$R_{i,r} = v_{kj}^{'} M_{w,i} \rho A \frac{\varepsilon}{k} \min_{R}\left(\frac{Y_R}{v_{R,r}^{'} M_{w,R}}\right) \tag{11}$$

$$R_{i,r} = v_{i,r}^{'} M_{w,i} \rho AB \frac{\varepsilon}{k} \frac{\sum pY_p}{\sum_j^N v_{j,r}^{''} M_{w,j}} \tag{12}$$

where: Y_p and Y_R are mass fraction of species, A is Magnussen constant for reactions (default 4.0), B is Magnussen constant for products (default 0.5), $M_{w,i}$ is molecular weight, *(R)* is reactans, *(P)* is products.

3. CHARACTERISTIC OF INVESTIGATED SYSTEM

Model-based tests aiming to assess the effects of an exogenous fire caused by methane combustion were used to analyse the mined dog heading along with the adjacent headings. The geometrical model of the headings under analysis, with a marked point in which methane combustion occurred, as well as with indicated flow directions for air and fire gases, has been presented in Figure 1.

The section of the mined dog heading was 25.0 metres long, and the outlet of air from the air duct was located at the distance of 4.0 metres from the front side of the mined face. The air flowing out of the mines heading changes its flow angle by 90° and flows along the dog heading. Based on the results of the measurements, it was assumed that air would be supplied to the mined heading face through the air duct with a diameter of 1 meter, at the speed of 4.0 m/s, with the oxygen content in this air being 21%. The temperature of the rock mass was 32℃.

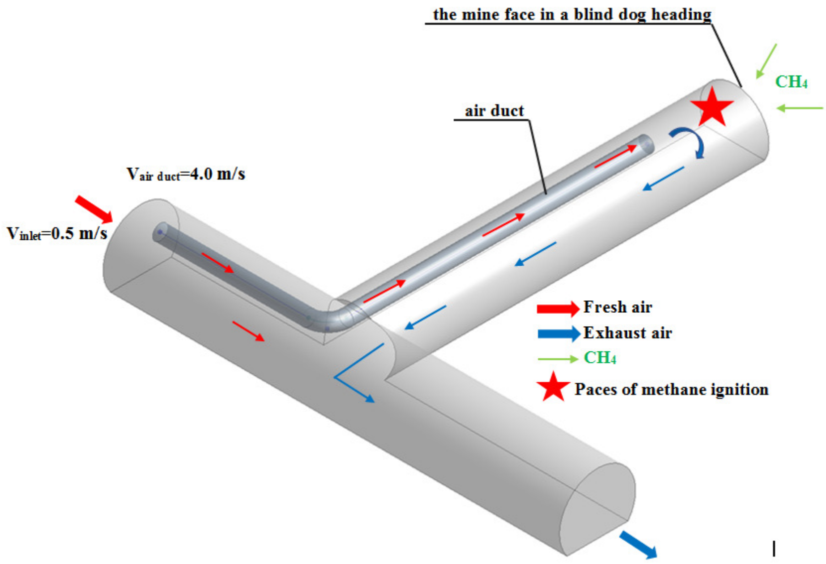


Fig. 1. The geometrical model of the headings with a marked point in which methane combustion occurred

While modelling methane combustion, it was assumed that the source of heat (the burning methane) would release a mass flow of gases into the air, including the products of the combustion process. The gases emitted into the atmosphere as a result of this process include carbon monoxide and carbon dioxide. The model in question made it possible to determine the concentration levels of fire gases in the air stream as well as the changes in its physical parameters in the analysed system of headings.

4. THE RESULTS

Based on performed calculations, distributions of changes of concentration of gases and temperature of air stream flowing through the dog heading with a fire center were determined. In order to present these distributions, nine measurement points were adopted in the system of headings under analysis. Their locality has been presented in Figure 2. The flow trajectories of the mixture of air and fire gases through the system of headings have been presented in Figure 3.

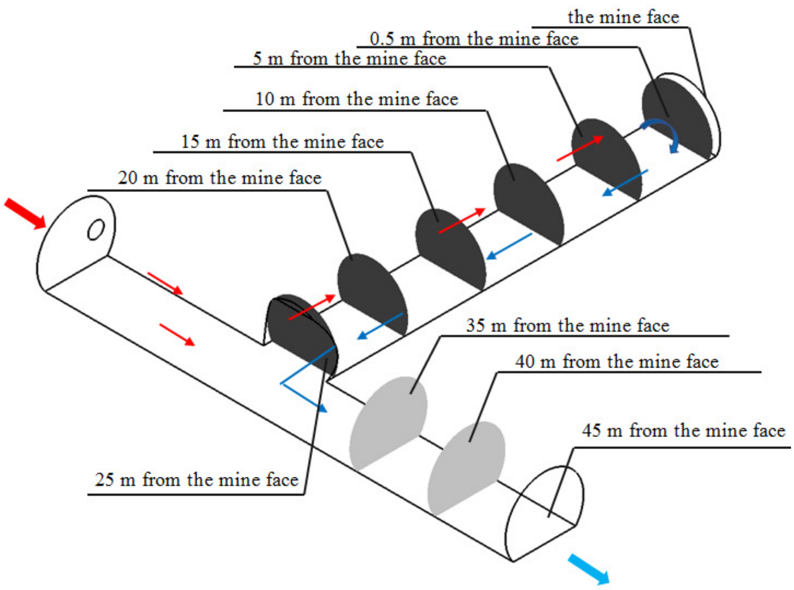


Fig. 2. Distribution of measurement points in headings

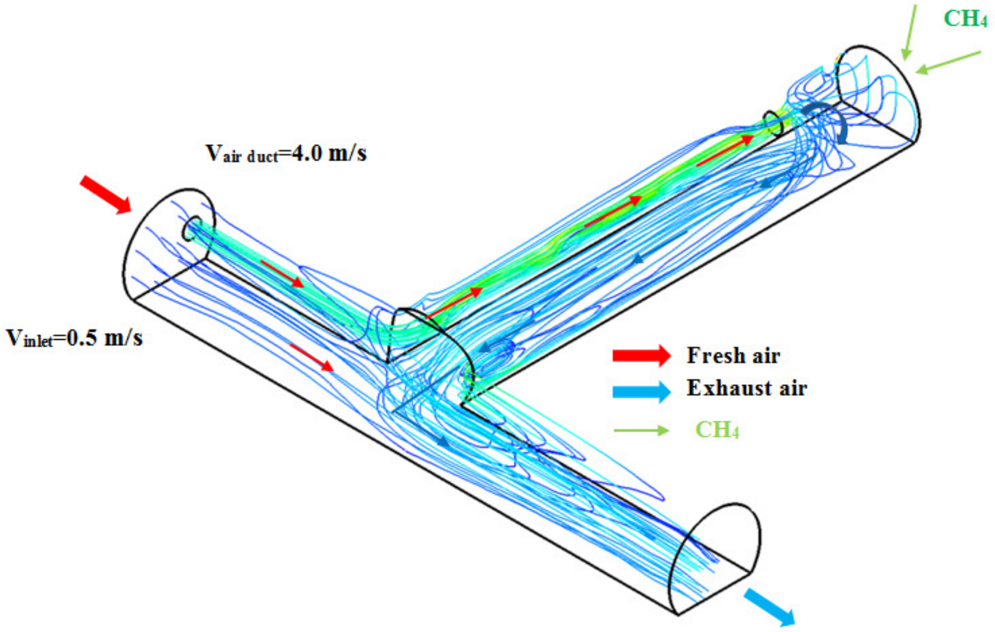


Fig. 3. The flow trajectories of the mixture of air and fire gases through the system of headings

In figure 4 there are presented characteristics of concentrations of oxygen, carbon monoxide and carbon dioxide in dog heading. Figure 5 presents the changes in the average temperature of the mixture of air and combustion products flowing through the system of headings under analysis. On the other hand, Figures 6-7 present the distributions of oxygen and carbon dioxide concentrations in the analysed system of headings.

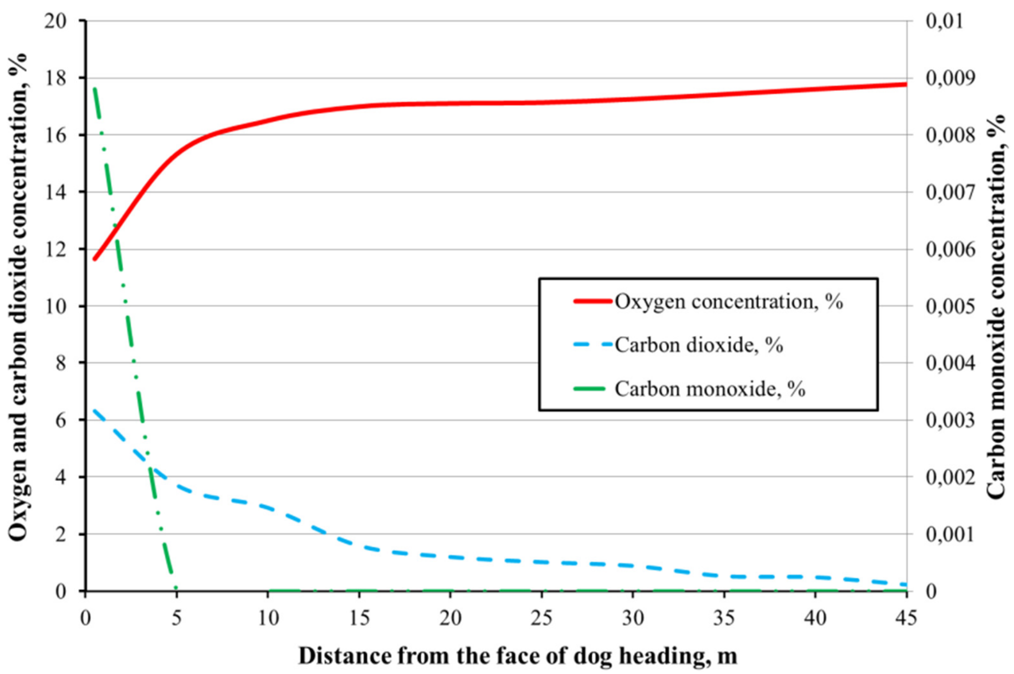


Fig. 4. Characteristics of concentrations of oxygen, carbon monoxide and carbon dioxide in dog heading

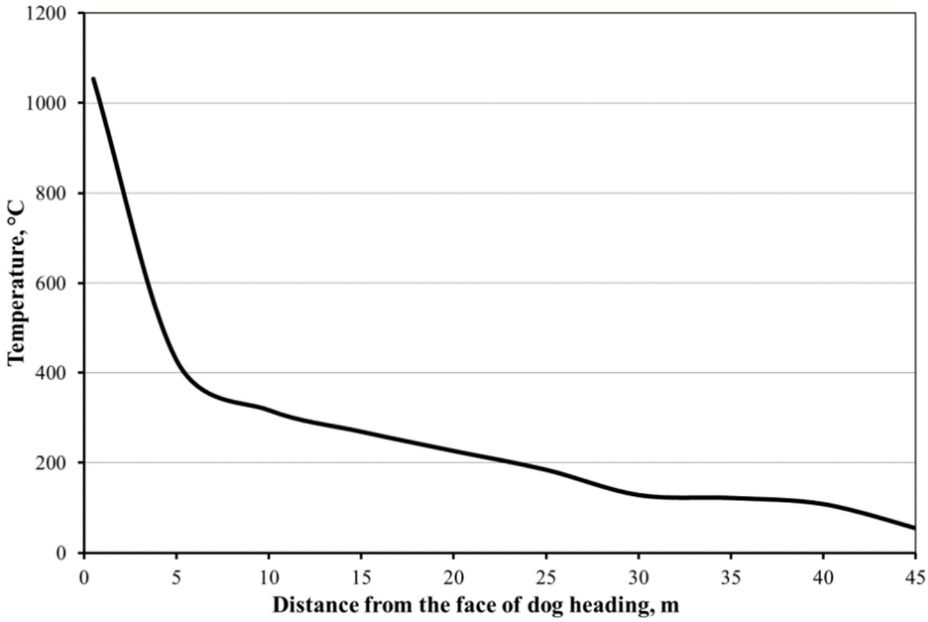
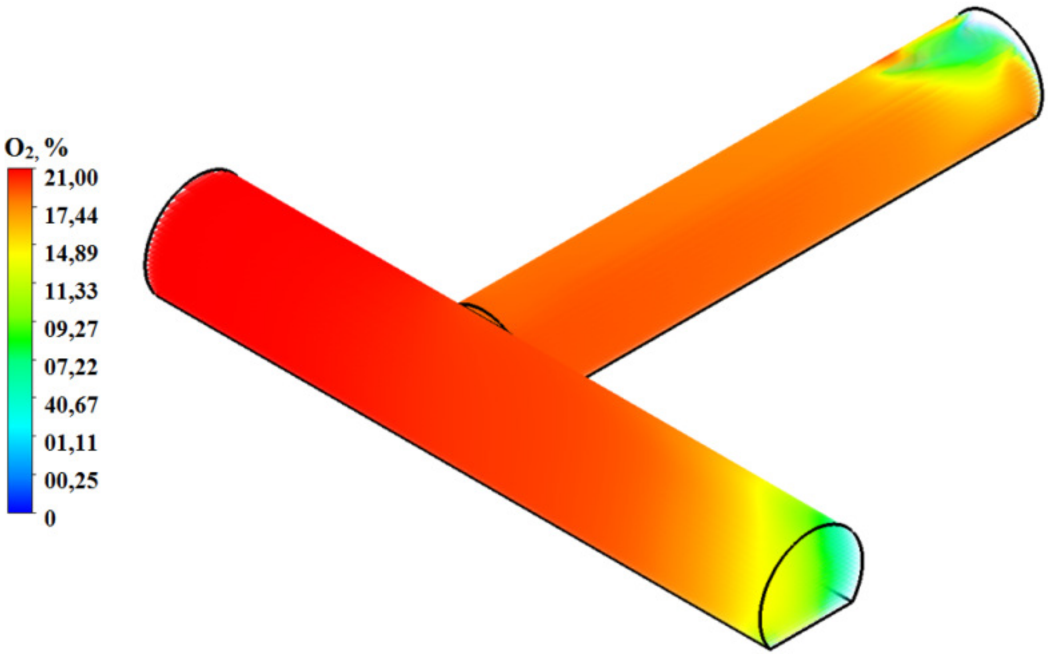


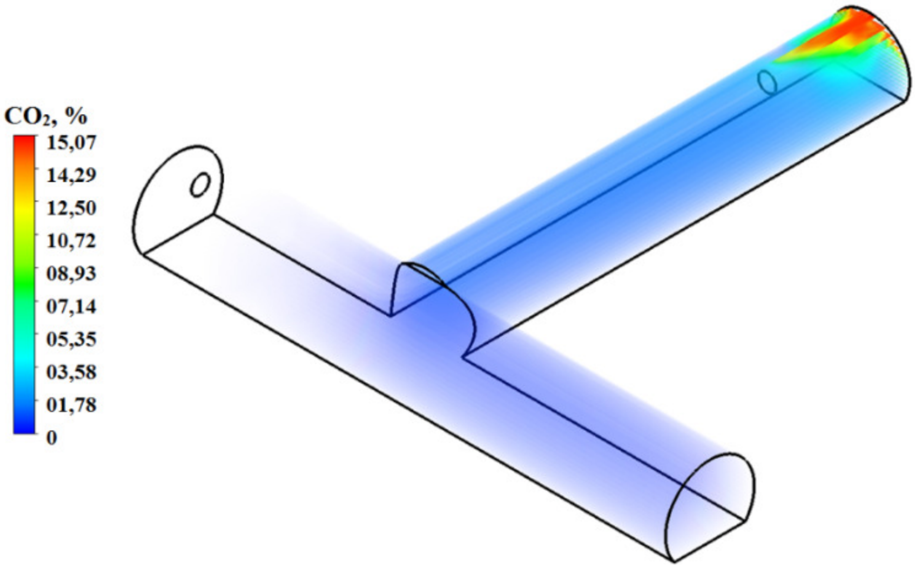
Fig. 5. The changes in the average temperature of the mixture of air and combustion products flowing through the system of headings

The analyses indicate that, in the case where small amounts of air are supplied into the heading, the temperature of the mixture of air and gases flowing through this heading is very high.

The calculations demonstrate that the highest concentrations of gases generated during combustion, i.e. carbon monoxide and carbon dioxide, occur directly over the source of fire. Along with the growing distance from the source of the burning gas, the temperature of the gases and the concentration levels of carbon oxide and carbon dioxide decrease, while the concentration of oxygen in the air stream increases.



Rys. 6. The distributions of oxygen concentrations in the analysed system of headings



Rys. 7. The distributions of carbon dioxide concentrations in the analysed system of headings

5. CONCLUSION

The methodology developed and the results obtained indicate that model-based tests can be successfully used for analysing fire events in mine headings. They make it possible to precisely determine the distributions of the physical and chemical parameters of the mixture of gases generated during fires. It is virtually impossible to measure these parameters in real world conditions.

Analysing the results obtained, one can conclude that exogenous fires are extremely dangerous as their effects spread rapidly across the entire region where they occur. This particularly concerns fire gases and high temperature. A significant danger is also posed by the presence of smoke in these headings. Fires in mine headings are therefore extremely dangerous phenomena that pose a serious threat to crew safety and production continuity. Having analysed the effects of an exogenous fire caused by methane combustion, it can be concluded that its occurrence considerably disturbs the ventilation process of mine headings. Once it has occurred, it is important to immediately close off the flow of air into the fire zone and extinguish the fire.

Therefore, it can be assumed that simulation methods based on computational fluid dynamics could be significant tool in improvement of the occupational safety in the mining. Obtained results clearly proof that numerical methods, combined with the results of tests in real (partial) conditions can be successfully used for the analysis of variants of processes related to ventilation of underground mining headings, and also in the analysis of emergency states.

Due to limitations of space in the publication, it only contains part of the vast research material obtained during the analyses.

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REFERENCES

Brodny, J. and Tutak, M. (2016a). Analysis of methane emission into the atmosphere as a result of mining activity. Proceedings of 16th International Multidisciplinary Scientific GeoConference SGEM 2016, DOI: 10.5593/SGEM2016/HB43/S06.012.

Brodny, J. and Tutak, M. (2016b). Analysis of gases emitted into the atmosphere during an endogenous fire. Proceedings of 16th International Multidisciplinary Scientific GeoConference SGEM 2016, pp. 75-82. DOI: 10.5593/SGEM2016/HB43/S06.011.

Brodny, J. and Tutak, M. (2016c). The impact of the flow volume flow ventilation to the location of the special hazard spontaneous fire zone in goaf with caving of operating longwalls. SGEM 2016, pp. 897-904. DOI:10.5593/SGEM2016/B12/S03.115.

Brodny, J. and Tutak, M. (2018). Analysis of methane hazard conditions in mine headings. Tehnički vjesnik/Technical Gazette, Vol. 25/No.1, pp. 271-276. DOI:10.17559/TV-20160322194812.

Brodny, J. and Tutak, M. (2018b). Determination of the Zone with a Particularly High Risk of Endogenous Fires in the Goaves of a Longwall with Caving. Journal of Applied Fluid Dynamics, Vol. 11, No. 3, pp. 545-553. DOI: 10.18869/acadpub.jafm.73.246.27240

Korban, Z. (2015). Quality assessment of occupational health and safety management at the level of business units making up the organizational structure of a coal mine: a case study. Int. J. Occup. Saf. Ergon. vol. 21 iss. 3, pp. 373-381.

Magnussen, B. F. and Hjertager, B. H. (1976). Sixteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh.

Sobieski, W. (2011). The basic equations of fluid mechanics in form characteristic of the Finite Volume Method. Tech. Sci., 14(2), 299-313.

Wang, P. (2016). The model constant A of the eddy dissipation model. Progress in Computational Fluid Dynamics An International Journal 16(2):118. DOI:10.1504/PCFD.2016.075154

WUG (2008-2017). The state of occupational health and safety in the mining industry. Katowice, [online] Available at: http://www.wug.gov.pl/ (Accessed 25 May 2018).