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NUMERICAL ANALYSIS OF AIRFLOW AND METHANE EMITTED FROM THE MINE FACE IN A BLIND DOG HEADING

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Abstract:
Ventilation is one of the most common presented problems during the driving of dog headings. During driving such heading has only one connection with air stream routes, which significantly make difficult the process of its ventilation. In a case of its driving in coal in the methane seam, this heading is endangered also to methane emission. In such case process of its ventilation is much more difficult. In the paper there are presented results of numerical analysis of ventilation of blind dog headings using air-duct forcing the air into its mine face. The analysis was performed for four different velocities of the air at the outlet from air-duct. The calculations were made for the excavation of heading with heading machine and conveyor belt.

Key words: *methane hazard, ventilation of dog headings, numerical analysis*

INTRODUCTION

Underground coal exploitation is dangerous due to many natural and technological hazards. One of the most common and most dangerous natural hazards is methane hazard. In the last few years in global mining industry as a result of explosion and inflammation of methane, there have been many disasters, in which many thousands of miners were subjected to accidents [6, 7, 10, 11].

In Polish hard coal mining, methane hazard is one of the most commonly present risks. In the years 2005-2014 in Polish mines 28 hazardous events associated with methane hazard took place (inflammation and explosions of methane), of which 8 occurred in a driven dog headings [5].

Driven dog headings are blind headings, *i.e.* they have only one connection with the air flow routes, which causes significant difficulties in their ventilation process. In a case of implementation of these headings in coal in the methane seam, they are additionally exposed to the release methane from the mine face, side walls, roof and floor of driven part, what additionally complicates their ventilation process [9].

Fighting methane hazard in the mine face of driven sidewalks is done primarily by preventing the accumulation of dangerous amounts of methane which causes its explosive concentrations. The main aim of this process is to supply to the mine face such amount of ventilation air that ensures that the methane concentration will not exceed the allowed value. To achieve this aim, stream of fresh air supplied to mine face of driven heading should have proper physical parameters and chemical composition. These parameters should be chosen so that the atmosphere formed in the heading assures demanded parameters necessary for exploitation works.

In order to fulfill these requirements, a stream of fresh air can be supplied to the blind mine face of dog heading by air-duct, depending on its length, angle of inclination and category of methane hazard, using additional ventilation devices or by diffusion [13].

Methods of ventilation of the blind heading are presented in Figure 1.

In practice, the most common ventilation of sidewalks during their execution, is carried out by supplying fresh air directly to their mine faces using an air-duct. Ventilation using air-ducts may be of negative pressure, positive pressure, or combined type (Fig. 1c) [15, 16].

In a case of methane hazard in headings, the positive pressure type of ventilation is being used, which is characterized by feeding more air than the exhaust ventilation, making it more effective (Fig. 2) [14, 15, 16, 17].

According to [13] velocity of air stream in the headings ventilated by duct lines in methane fields in 2nd category of methane hazard cannot be less than 0,30 m/s.

In non-methane fields and classified in 1st category of methane hazard, this velocity must be at least 0,15 m/s. Simultaneously, velocity of air stream in dog heading does not exceed 8,0 m/s [13].

It can be assumed, that the velocity of the air flow supplied to the driven mine face of dog heading should be such that limit TLV of methane is not exceeded and simultaneously, the safety of the working crew is provided.

Therefore, it is appropriate to conduct research in order to determine parameters of the air stream flowing through the blind dog heading considering methane evolving from the mine face of this heading. Such research can be carried out in underground conditions as well as with use of simulation methods [3, 8, 9, 12]. In recent years, these methods are widely used to analyze the ventilation problems. However, not many researches include three-dimensional analysis considering the methane hazard.

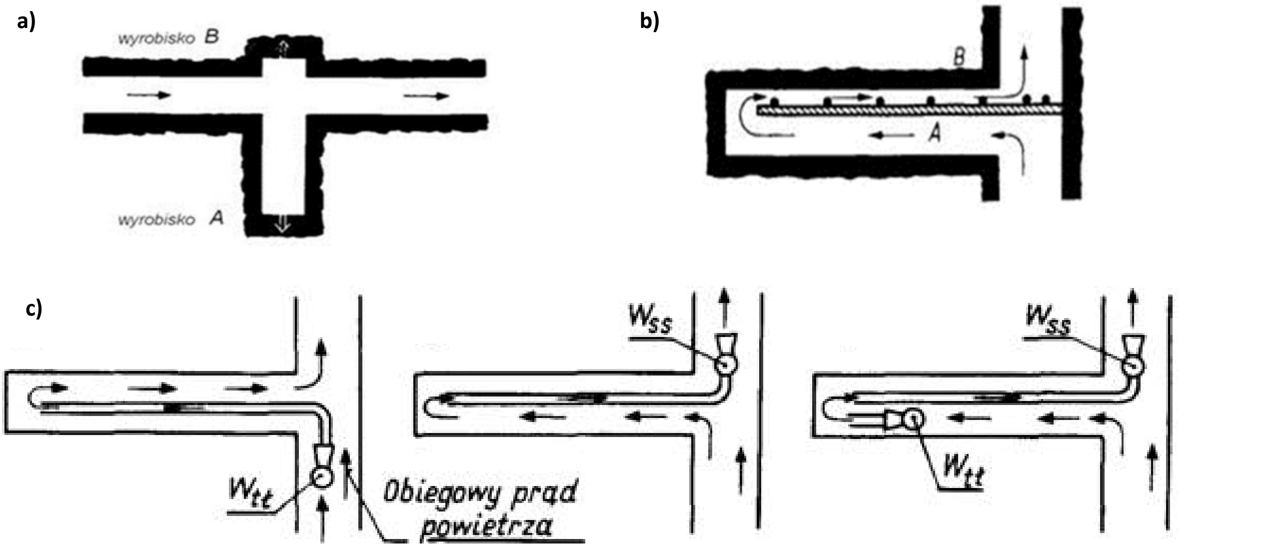

Fig. 1 Methods of ventilation of the blind heading:
a) by diffusion, b) using additional ventilation devices, c) by air-duct (pressuring ventilation, suction ventilation, press-suction combined ventilation)
Source: [2].

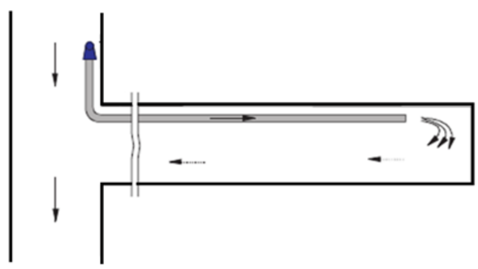

Fig. 2 Scheme of pressuring ventilation
Source: [2].

Also due to this regard, this paper presents the results of numerical research which aims to analyze the air flow and methane evolution from the mine face in blind dog heading ventilating by positive pressure air-duct.

The aim of the study was to determine the effect of velocity of air stream supplied by air-duct to mine face of dog heading from which methane is emitted, on distribution its concentration in this heading.

Calculations were performed for transient flow in the heading equipped with air-duct, heading machine and belt conveyor.

THE MATHEMATICAL MODEL OF THE FLOW

Computational Fluid Dynamics (*CFD*) is a simulation method of processes connected with flow of liquids and gases, heat and mass transfer, or chemical reactions [19].

Software based on the Computational Fluid Dynamics (CFD) allow to obtain necessary information, concerning the mass flow of air stream or liquid (distribution of velocity field, distribution of pressure field), heat transfer (temperature field), and also the physical-chemical changes.

In the study, the physical and chemical parameters of air and methane mixture flowing through the driven heading ventilated by positive pressure air-duct were determined using the ANSYS Fluent software.

Turbulent flow of a viscous, incompressible fluid is described by Navier-Stokes system of equations, which together with the continuity equation are complete relationship system, which allows determining pressure and the flow velocity field [19].

Problems connecting with fluid transport in this software are solved basing on following fluid mechanics and thermodynamic equations [1]:

– he continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = S_m \tag{1}$$

where:
$\vec{v}$ – 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

– momentum equation

$$\frac{\partial \rho}{\partial t}(\rho \vec{v}) + \nabla(\vec{v}\vec{v}) = -\nabla p + \nabla(\bar{\tau}) + \rho \vec{g} + \vec{F} \tag{2}$$

where:
p – static pressure, Pa
$\bar{\tau}$ – the stress tensor, Pa
$\vec{g}$ – the gravitational body force, m/s^2
$\vec{F}$ – the external body force, N

– energy equation

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

where:
E – total energy, J/kg
k_{eff} – the effective conductivity, W/(mK)
T – temperature, K
h_j – entalpia właściwa j-tego składnika mieszaniny, J/kg
τ_{eff} – turbulent stress tensor, Pa
$\vec{J}_i$ – the diffusion flux of species, kg/(m^{2}s)
S_h – the heat of chemical reaction, W/m^3

Transport equation determining the local mass loss for each component of the mixture and the diffusion equation takes the following form:

– species transport eguation

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i \quad (4)$$

where:

Y_i – the local mass fraction of each species

$\vec{J}_i$ – the diffusion flux of species *i*, kg/(m^2s)

R_i – the net rate of production of species *i* by chemical reaction

S_i – the rate of creation by addition from the dispersed phase plus any user-defined sources

– mass duffusion in turbulent flows

$$\vec{J}_i = -(\rho D_{i,m} + \frac{\mu_t}{Sc_t})\nabla Y_i \quad (5)$$

$D_{i,m}$ – the mass diffusion coefficient for species *i* in the mixture, m^2/s

μ – the viscosity, Pa·s

S_{Ci} – the turbulent Schmidt number, 0.7

Presented model connects description of the airflow and gases transport, and also the heat exchange.

Flow of air stream through the driven dog heading ventilated by air-duct has turbulent character, in which there is an irregular movement of air molecules, and the parameters of its flow experience unpredictable random changes in space and time [18]. Turbulence of flow is characterized by three-dimensionality, diffusivity, as well as randomness, cascade and hierarchization of vortices [4].

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:

a) k-transport equation

$$\rho\frac{\partial k}{\partial t} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \mu_t S^2 - \rho\varepsilon \quad (6)$$

b) ε-transport equation

$$\rho\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}\left(C_{1\varepsilon}\mu_t S^2 - \rho C_{2\varepsilon}\varepsilon\right) \quad (7)$$

where:

$C_{1\varepsilon}$, $C_{2\varepsilon}$ – constans,

∂_k, ∂_ε – turbulent Prandtl numbers for k and ε,

S – user-defined source terms.

ANALYSIS OF THE FLOW

Driven dog heading was subjected to analysis. It was assumed that this heading is supplied by fresh air from forced duct line, and methane is emitted from its mine face.

In such a case, the task of the ventilation process, besides providing sufficient amount of oxygen for the operating crew, is to prevent exceeding the permissible methane concentration (2%) in the mixture with air. This aim is achieved by providing through an air-duct to the driven mine face an air stream with specified parameters.

The flow model

In order to perform an analysis, geometrical model of this heading with air-duct, conveyor belt and heading machine was developed (Fig. 3).

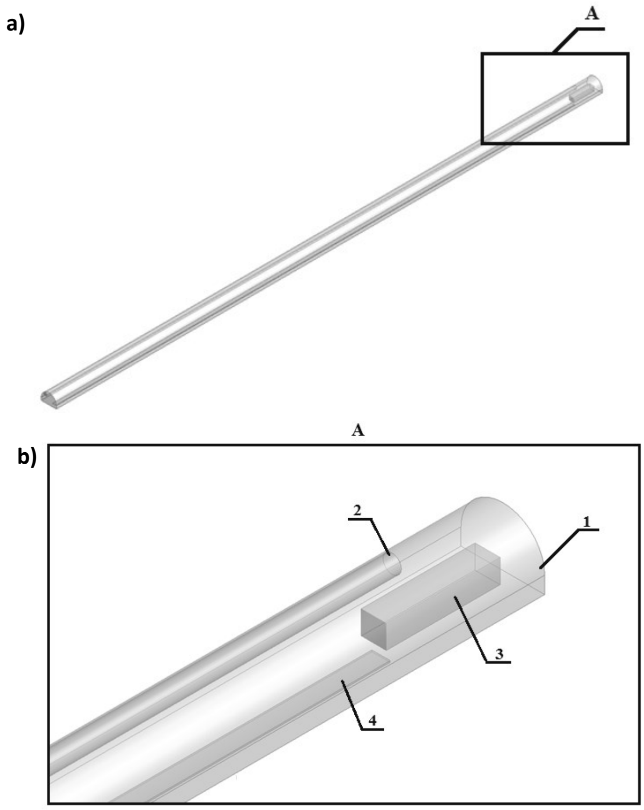

Fig. 3 Models of mining headings
1 – surface emission of methane, 2 – the air-duct
3 – the heading machine, 4 –the conveyor belt

For the model it was assumed that the length of side-walk equals to 200 m, the length of the air-duct equals to 194 m, whereas length of belt conveyor equals to 190 m. It was assumed that heading has width of 5.5 m and 3.85 m of height (S = 17.93 m^2). It was assumed that the conveyor is at a height of 1 m, and its width equals 1.2 m. Heading machine was modeled in a form of a cuboid with dimensions 7.47x1.645x1.65 m.

Analysis was performed using physical models *k – ε standard* and *species transport*.

As an "inlet" boundary condition, a constant velocity field of air forced through the air-duct to the driven heading was assumed. It was assumed also that velocity of forced air stream through air-duct will be: 25, 30, 35 and 40 m/s.

For analyzed model, exit was defined as an "outlet" boundary condition, while the walls were defined as impermeable.

During modeling of methane emission from the face of mine face of driven heading, it was assumed the absolute methane content equals to 0.084 m^3/s. Time of analysis took 600 seconds.

The analysis results

Based on performed calculations the characteristics of changes of velocity of air and methane mixture stream and distributions of methane concentration in this heading were determined.

In Figure 4 there is presented distribution of velocity of mixture stream along heading after 600 seconds, and in a Figure 5 – an average value of velocities of mixture stream at the outlet from the heading for different values of air stream velocity (*v*) forced through air-duct in a function of time analysis.

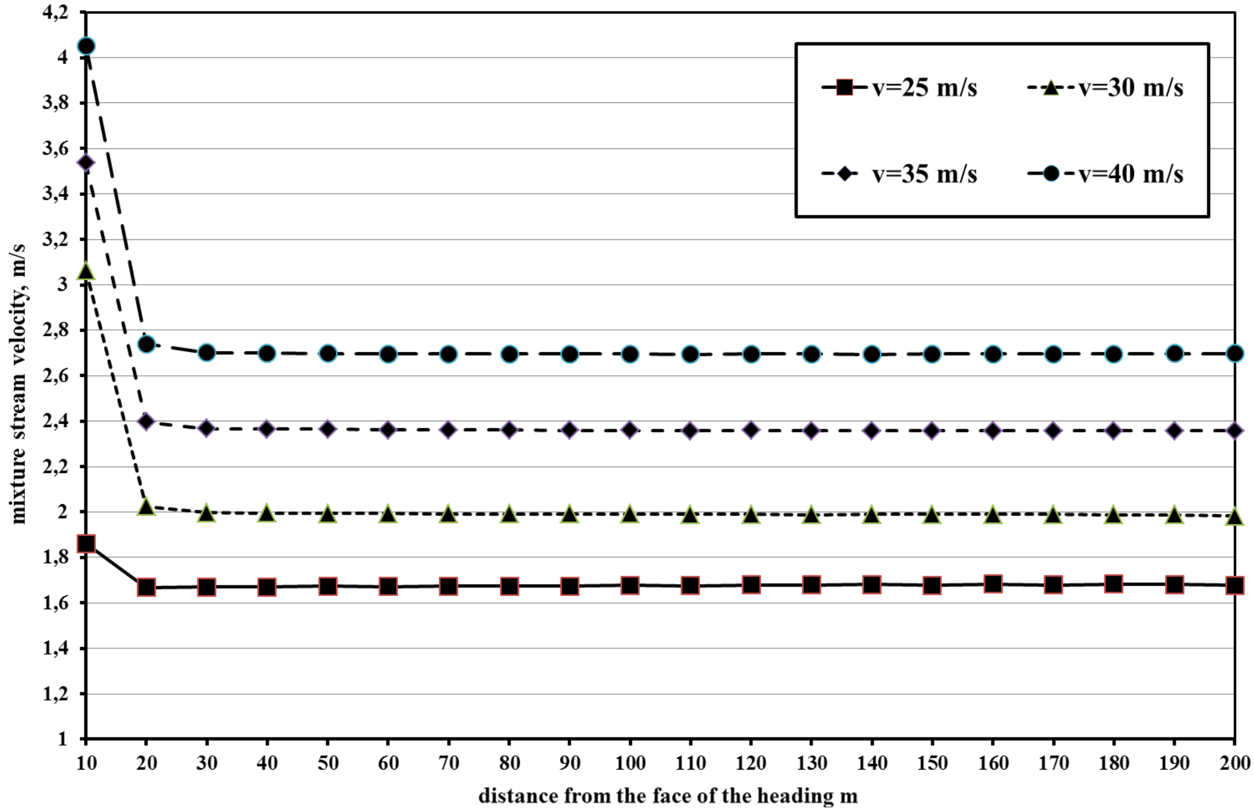

Fig. 4 Distribution of velocity of the mixture stream (v) along heading after 600 seconds for different values of air stream velocity

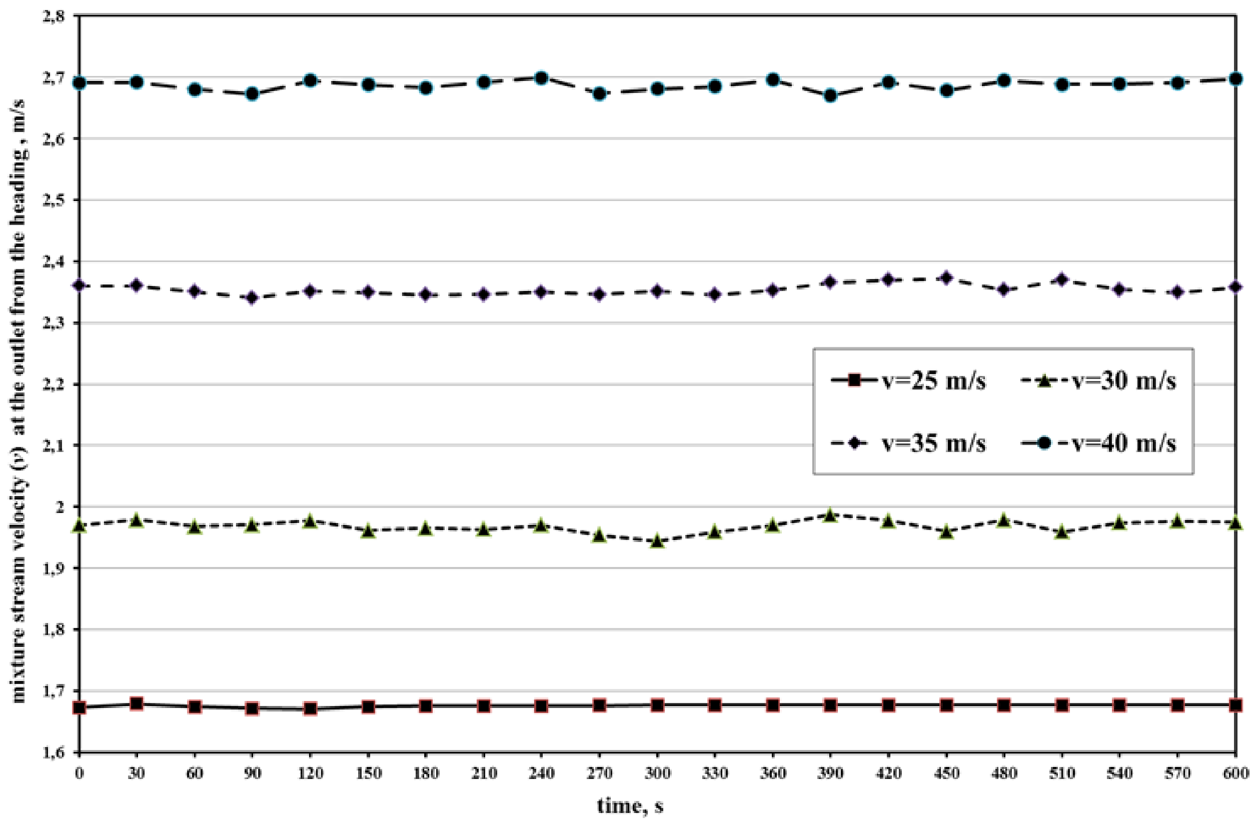

Fig. 5 Average value of velocities of mixture stream at the outlet from the heading for different values of air stream velocity (v) forced through air-duct in a function of time analysis

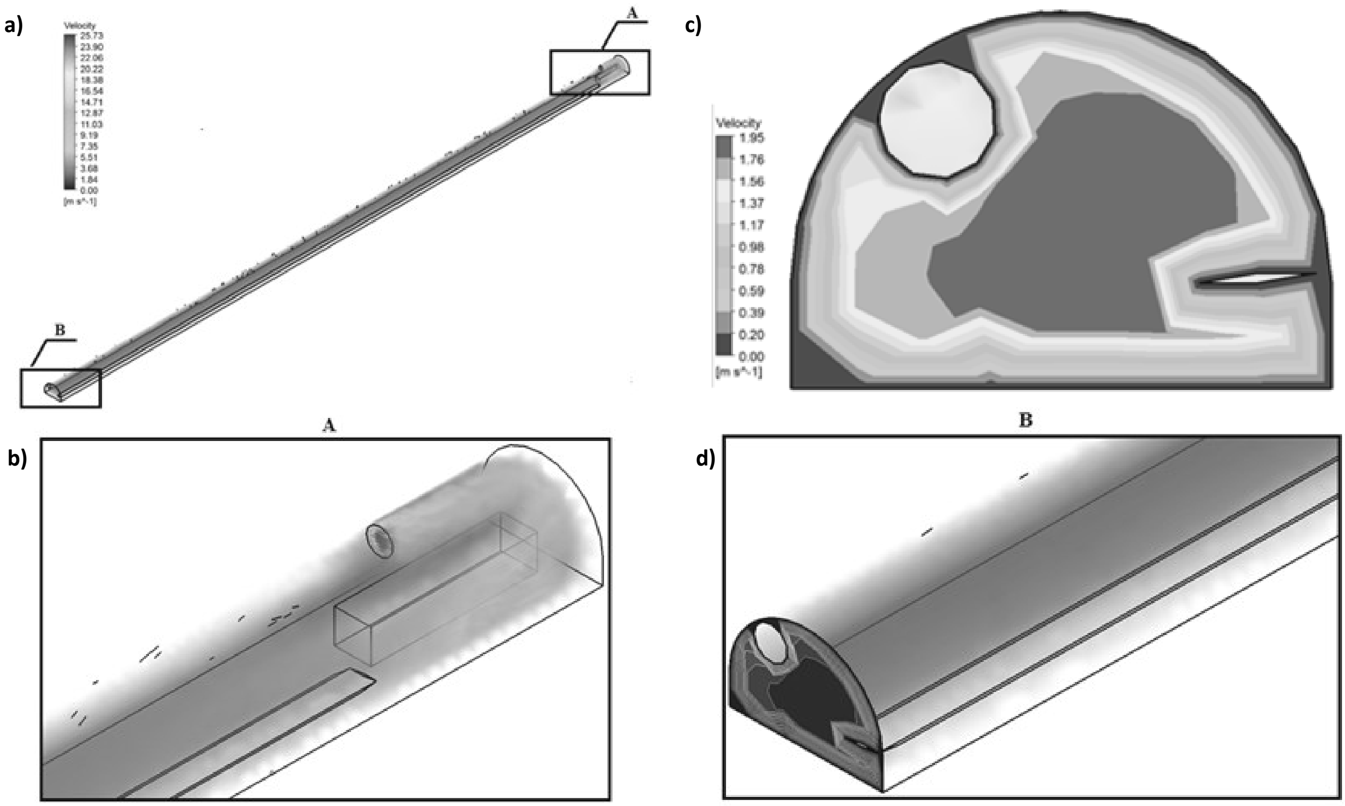

Fig. 6 Distributions of velocities of air and methane mixture in heading after 600 seconds of analysis for velocity of air stream at outlet from air-duct equals 25 m/s (a - in heading, b – in mine face, c - at outlet from heading, d – in outlet section from heading)

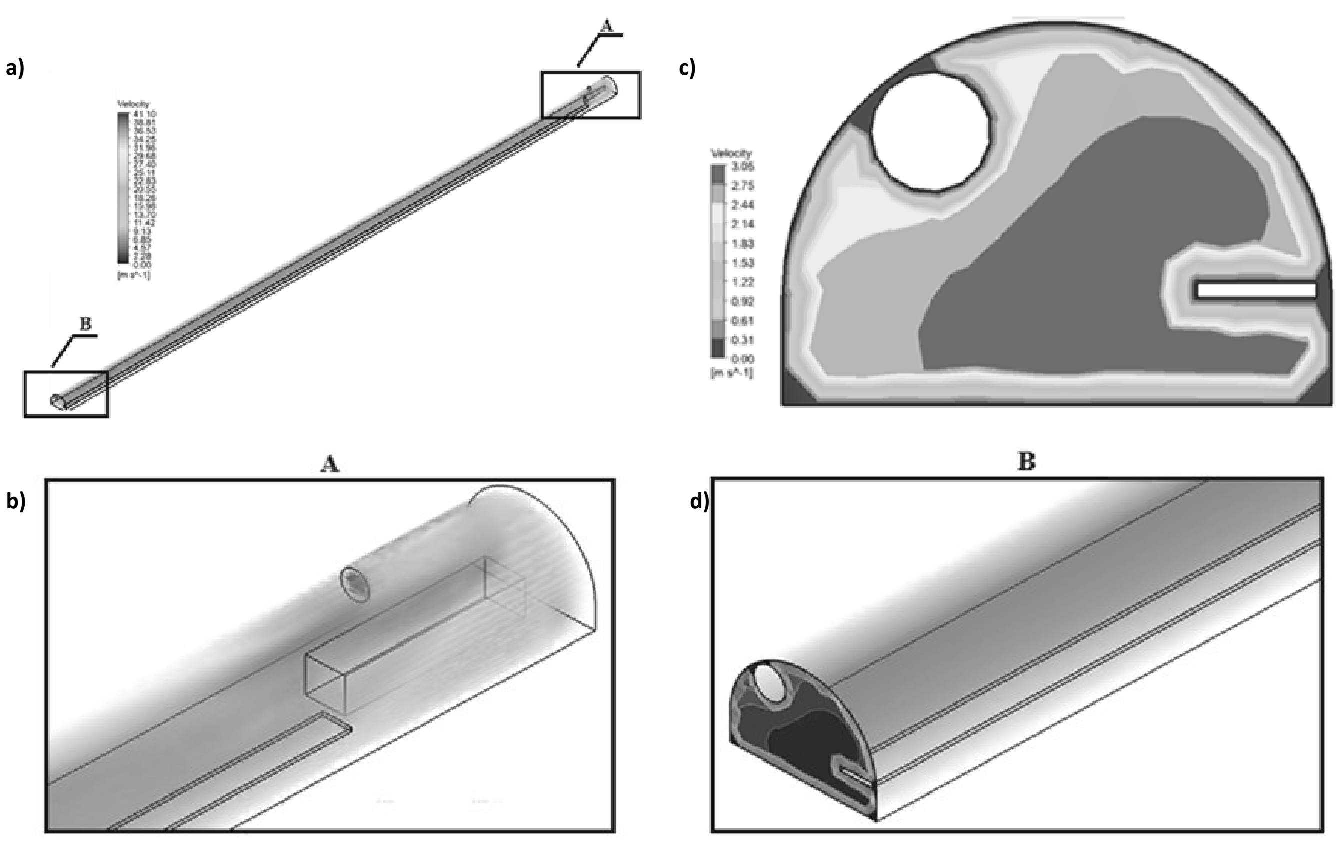

Fig. 7 Distributions of velocities of air and methane mixture in heading after 600 seconds of analysis for velocity of air stream at outlet from air-duct equals 40 m/s (a - in heading, b – in mine face, c - at outlet from heading, d – in outlet section from heading)

In Figures 6 and 7 distributions of vectors of velocity of the mixture for analyzed heading, for velocity at outlet from air-duct equal to 25 and 40 m/s are presented.

In Figure 8 there are presented changes of methane percentage concentration in the air mixture at outlet from heading in a function of time analysis, and in Figures 9 and 10 as function of distance from mine face.

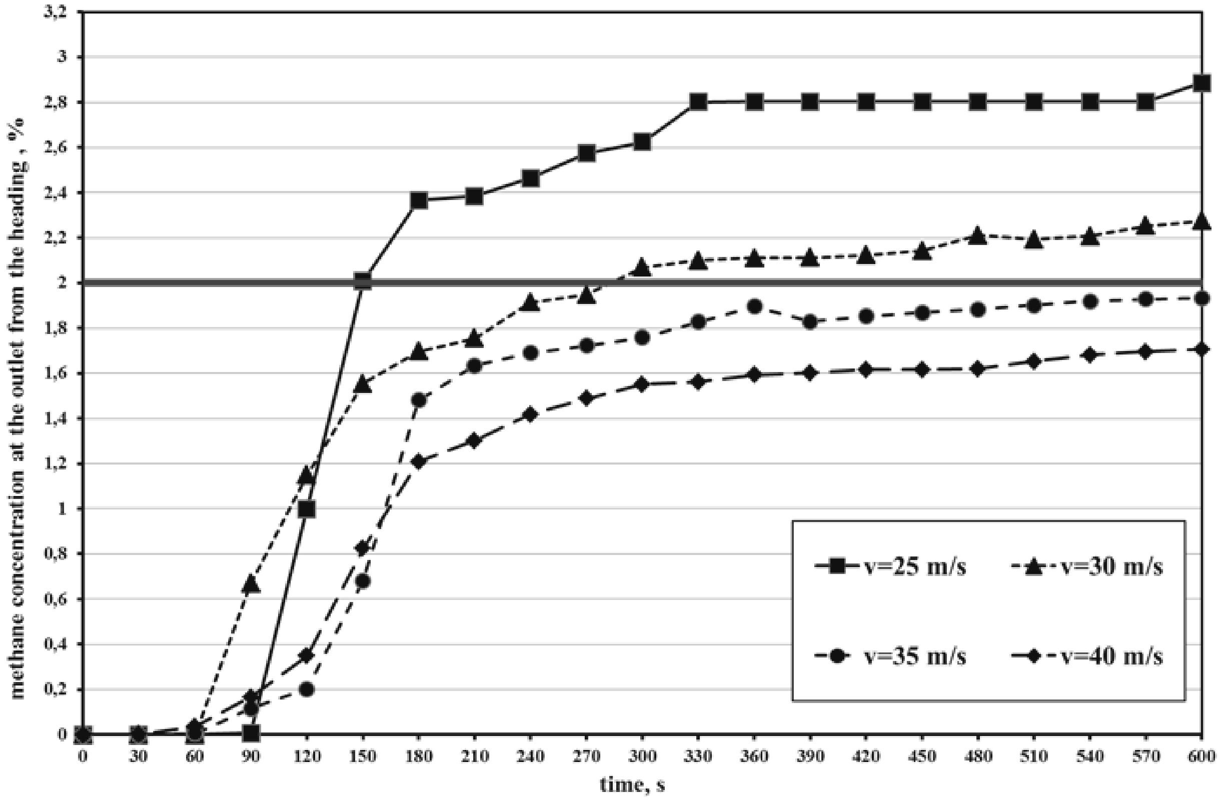

Fig. 8 Changes of methane percentage concentration in the air mixture at outlet from heading in a function of time analysis

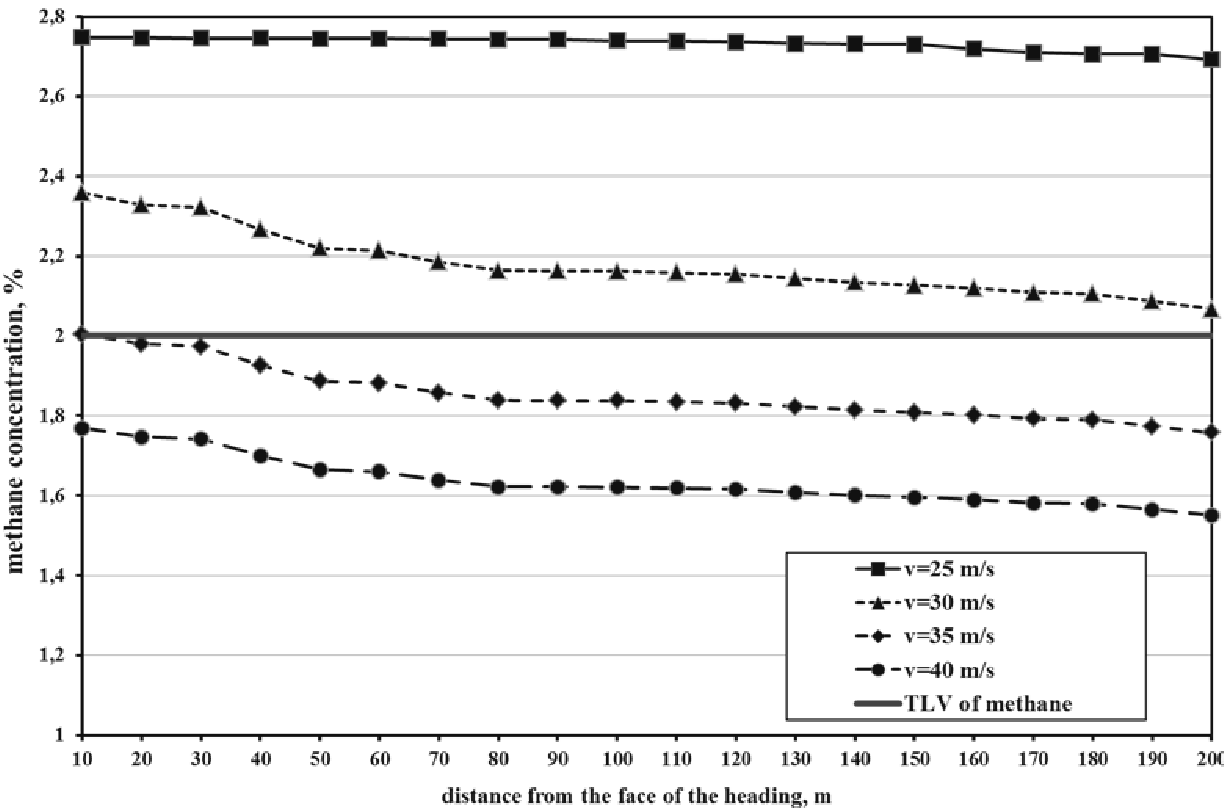

Fig. 9 Distribution of methane concentration along heading after 300 seconds for different values of air stream velocity

Performed analysis showed that the allowable methane concentration at the outlet from heading after 600 seconds, has not been exceeded at the stream velocity at the outlet of the air-duct equal 35 and 40 m/s. However, for velocity 25 and 30 m/s allowed value of methane concentration is exceeded faster as the air forced to air-duct stream velocity decreases. The highest methane concentration after 300 and 600 seconds of analysis, are observed in mine face of driven heading. As a distance from the mine face increases, methane concentration in the heading decreases. This dependence is valid for all considered stream velocities of air forced into the heading. Although, only for air stream velocity at the air-duct outlet equal to 40 m/s, methane in the heading concentration value does not exceed the allowed value of 2% after 300 and 600 seconds of analysis.

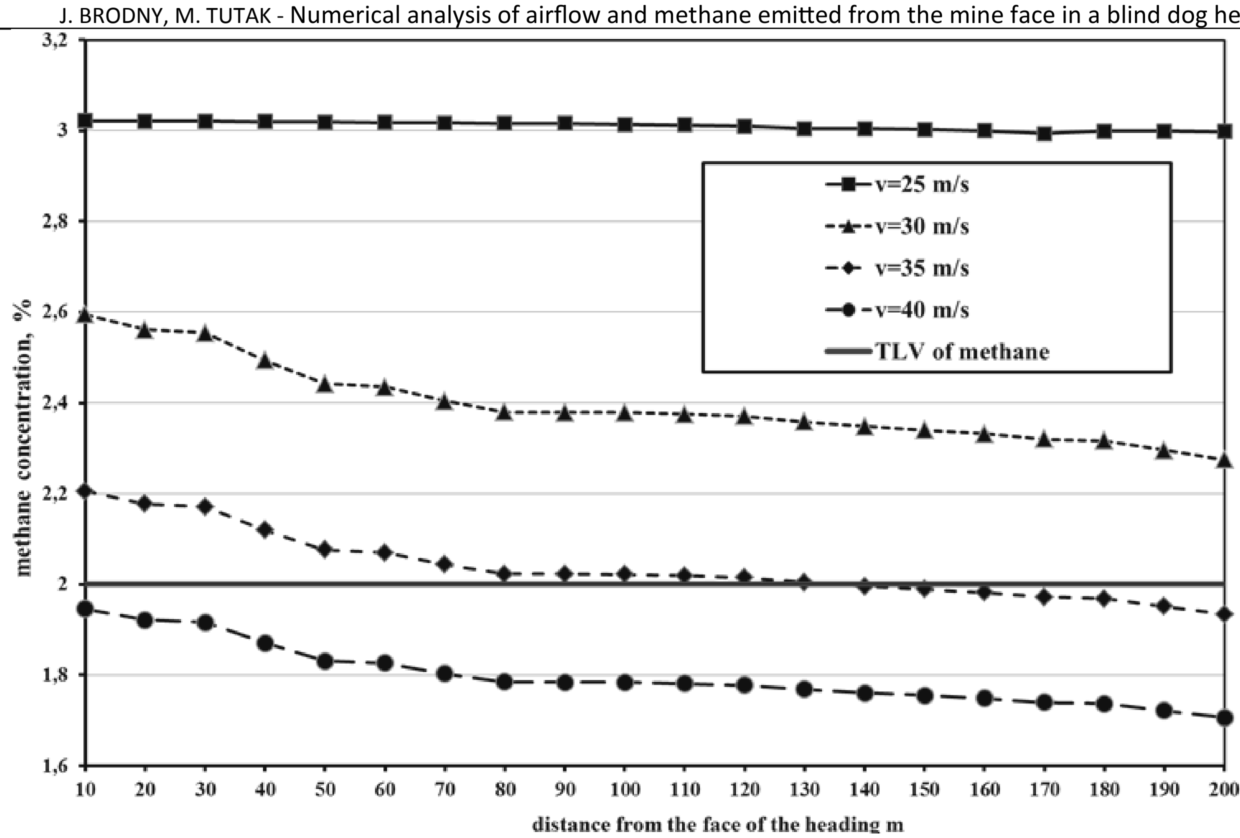

Fig. 10 Changes of methane percentage concentration in the air mixture at outlet from heading in a function of time analysis

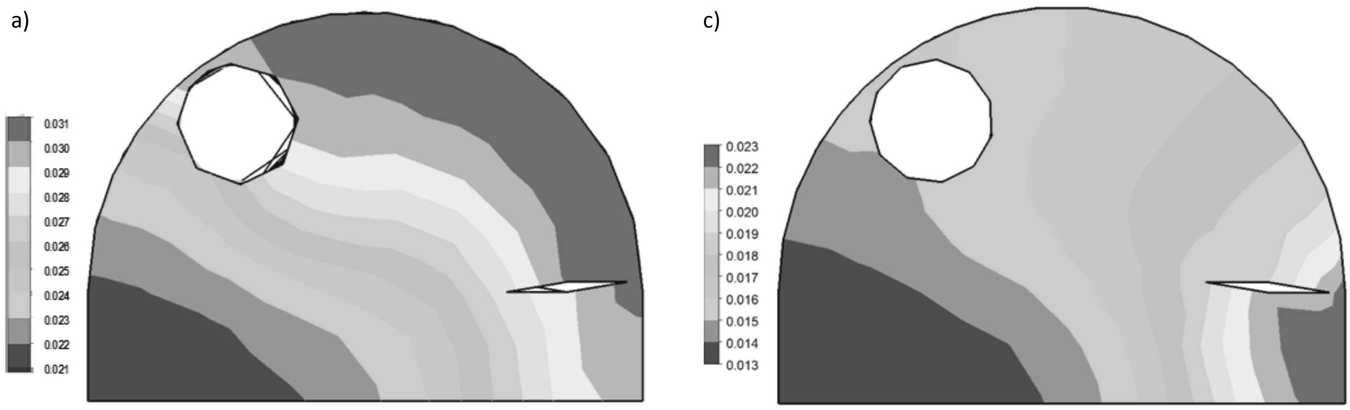

Fig. 11 Distribution of methane concentration in the mixture with air at outlet from analyzed heading after 600 seconds
a – distribution air stream supplied by air-duct to heading from velocity 25 m/s,
b - distribution air stream supplied by air-duct to heading from velocity 40 m/s

Therefore, it can be assumed that together with increasing time of methane emission from the mine face to the heading increases its concentration in entire heading.

In Figure 11 there is presented distribution of methane concentration in the mixture with air at outlet from analyzed heading for air stream supplied by air-duct to this heading from velocity equals 25 (Fig. 11a) and 45 m/s (Fig. 11b).

In Figures 12 and 13 there are presented distributions of methane concentration in mixture with air in distance 6, 50, 100 and 150 meters from mine face for air stream supplies by air-duct for this heading with velocity equals 25 m/s (Fig. 12) and 40 m/s (Fig. 13).

Performed analysis indicated that velocity of air stream forced through air-duct to the heading, has significant impact on methane concentration distribution along examined heading and in its cross-section depending on a distance from the mine face.

CONCLUSIONS

Developed and used model allowed to determine distribution of velocity of the mixture stream and methane concentration in heading.

Based on obtained results, one can conclude that air stream velocity at the outlet from air-duct has significant impact on the mixture velocity distribution in heading and on the methane concentration in this mixture. Together with increase of air stream velocity at the outlet from air-duct, methane concentration decreases along entire heading. It results from an increase of volumetric airflow rate incoming into heading.

The value of velocity of an air stream forced into the mine face of heading has also impact on methane concentration distribution along heading and in its cross-section. Obtained results confirm that methane accumulates at the roof of heading.

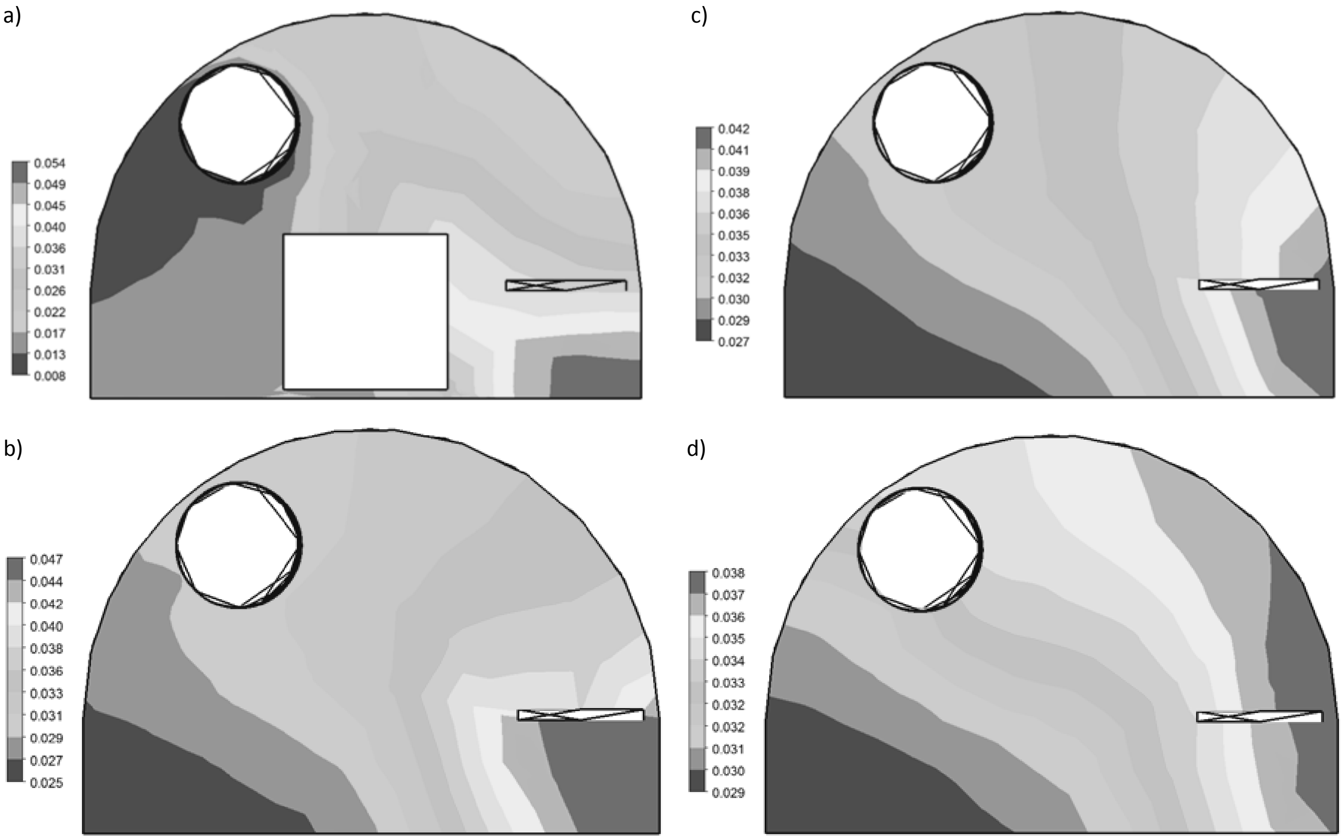

Fig. 12 Distribution of methane concentration in the mixture in cross-section excavation after 600 seconds for air stream supplies by air-duct with velocity equals 25 m/s
a – with in distance 6 m meters from mine face, b –with in distance 50 m meters from mine face,
c – with in distance 100 m meters from mine face, d – with in distance 150 m meters from mine face

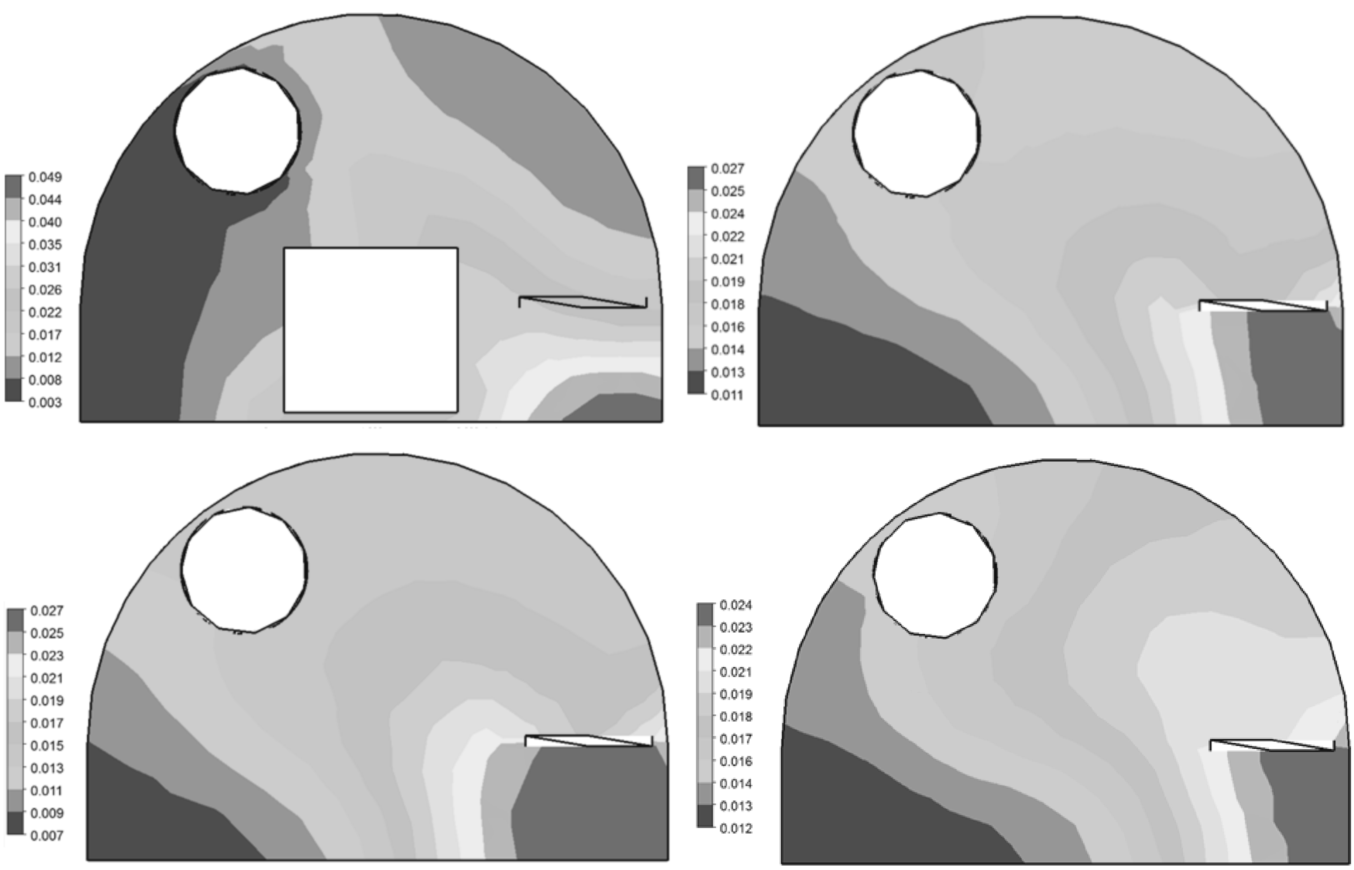

Fig. 12 Distribution of methane concentration in the mixture in cross-section excavation after 600 seconds for air stream supplies by air-duct with velocity equals 40 m/s
a – with in distance 6 m meters from mine face, b –with in distance 50 m meters from mine face,
c – with in distance 100 m meters from mine face, d – with in distance 150 m meters from mine face

Also at lower values of velocity of an air stream forced into the mine face of heading, there was observed considerable increases of methane concentration under belt conveyor, which values were higher than that at roof of a heading. In such cases it seems necessary to control methane concentration also under the belt conveyor.

Based on obtained results, one can precisely determine the value of fresh air and methane mixture velocity and methane concentration at analyzed heading at any moment and point in heading. This has significant meaning during determination of zone in headings, at which methane concentration could exceed allowed value.

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