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NUMERICAL SIMULATION OF DEVELOPMENT OF A FIRE IN THE LONGWALL GOAF

SYMULACJA NUMERYCZNA ROZWOJU OGNISKA POŻARU W ZROBACH ŚCIANY PROWADZONEJ NA ZAWAŁ STROPU

Issues related to the forecasting of the ventilation process developing in the mine ventilation after occurrence of an underground fire located in a longwall goaf resulted in the development of a method to determine parameters specifying the unstable condition that may develop in the mine ventilation network. This forecasting method was based on a numerical simulation of the ventilation process for the network of mine excavations. The mathematical model of the phenomena under consideration is a complex system of non-linear partial differential equations that are mutually interlinked by physical parameters and boundary and initial conditions. The phenomena described by the mathematical model may be divided into three basic categories:

1. Distribution of the mixture of air and gases and determination of the flow velocity of the mixture in excavations and goaf in relation to various ventilation conditions.
2. Changes in concentration levels of individual components of the mixture, taking into account varying flow velocity and sources of inflow of combustion gases in time.
3. Time and spatial distribution of the temperature of the fire itself and that of the surrounding goaf area.

In this paper a mathematical model of a fire in a goaf is presented, which includes the coal combustion process. The result of combustion is a fall in the oxygen content (2.1), which determines the flow-stream of the generated heat (2.12) and the stream of gases generated by the combustion (2.6). To specify the parameters in the equation that describes the coal combustion process, results of experimental research conducted in conditions of mine excavation were used (Dziurzyński, Tracz 1994). This mathematical model of the fire is presented in the form of cylindrical coordinates (3.8) permitting the for calculation of the fire temperature in the goaf, taking into consideration transport and conductivity of heat generated by the combustion process. Furthermore, absorption of heat by conductivity of the fire's surrounding environment (3.9) was included in the equation of the temperature distribution in the fire. For the mathematical model, boundary and initial conditions were determined for the model – equations (2.8), (3.8), (3.9). To obtain the solution, a numerical method was used based on the approximation of the non-overt (5.1) and overt (5.8), (5.11) differential models.

Two examples of simulation of development of the fire under different ventilation conditions are investigated. The results of the simulation are presented graphically as time diagrams (Fig. 10) and in a form of spatial distribution diagrams (Figs. 2 to 9).

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On the basis of the model and the numerically calculated solutions, it was concluded that the combustion process in the fire occurs mainly at the contact of its face with the inflowing air. As a result of the low flow velocity in the goaf, amounting only to a few mm/s, oxygen is consumed rapidly by the combustion process. The mine fire moves towards the inflow of fresh air, thus increasing in size both alongside and across the line of the flow-stream. The simulations performed indicate that there is a certain border value of flow velocity in the goaf, exceeding which results in a sudden development of the fire. This condition is characterised by an increase of the solid's radius, with an increased flow rate of the generated combustion gases. The calculated size of the mine fire is several metres and the shape of the solid that it forms resembles a falling drop of water.

Key words: mine ventilation, mine fire, computer simulations

Rozważania dotyczące prognozy procesu przewietrzania odbywającego się w sieci wentylacyjnej kopalni głębinowej po wystąpieniu pożaru podziemnego, zlokalizowanego w zrobach ściany prowadzonej na zawał stropu, doprowadziły do opracowania metody wyznaczania parametrów określających trudny do odgadnięcia stan, w jakim może znajdować się kopalniana sieć wentylacyjna. Metodę prognozowania oparto na symulacji numerycznej procesu przewietrzania sieci wyrobisk kopalni. Model matematyczny badanych zjawisk jest złożonym układem równań różniczkowych cząstkowych nieliniowych, wzajemnie sprzężonych parametrami fizycznymi i warunkami brzeżno-początkowymi. Model matematyczny opisuje zjawiska podzielone na trzy podstawowe działy:

1. Rozpływ mieszaniny powietrza i gazów oraz wyznaczenie prędkości przepływu mieszaniny w wyrobiskach i zrobach w zależności od zmieniających się warunków przewietrzania.
2. Zmiany stężeń poszczególnych składników mieszaniny z uwzględnieniem zmieniających się w czasie prędkości przepływu oraz źródeł dopływu gazów domieszkowych.
3. Rozkład czasoprzestrzenny temperatury ogniska pożaru i otaczającego go obszaru zrobów.

W artykule przedstawiono model matematyczny ogniska pożaru w zrobach, który uwzględnia proces spalania węgla. Skutkiem procesu spalania następuje ubytek tlenu (2.1), co determinuje strumień wydzielanego ciepła (2.12) oraz strumień wydzielanych gazów pożarowych (2.6). Dla wyznaczenia parametrów w równaniu opisującym proces spalania węgla wykorzystano badania eksperymentalne przeprowadzone w warunkach wyrobiska górniczego (Dziurzński, Tracz 1994). Przyjęty model matematyczny ogniska pożaru, podany we współrzędnych walcowych (3.8), pozwala na obliczenie temperatury ogniska pożaru w zrobach z uwzględnieniem transportu i przewodnictwa ciepła wydzielonego w procesie spalania węgla. Ponadto w równaniu rozkładu temperatury w ognisku pożaru uwzględniono odbieranie ciepła przez przewodnictwo do otaczającego ognisko pożaru środowiska (3.9). Dla modelu matematycznego wyznaczono warunki brzeżno-początkowe dla równań modelu (2.8), (3.8), (3.9). Dla uzyskania rozwiązania przyjęto metodę numeryczną opartą na aproksymacji schematem różnicowym niejawnym (5.1) oraz jawnym (5.8), (5.11).

Przedstawiono dwa przykłady symulacji rozwoju ogniska pożaru przy zmiennych warunkach przewietrzania. Wyniki symulacji pokazano w postaci graficznej na wykresach czasowych (rys. 10) i w postaci rozkładów przestrzennych (rys. 2–9).

Na podstawie przedstawionego modelu i uzyskanych numerycznie rozwiązań stwierdzono, iż w ognisku pożaru proces palenia w dużej mierze zachodzi na styku jego czoła z napływającym powietrzem. Wskutek niewielkich prędkości przepływu w zrobach (rzędu mm/s), tlen jest szybko zużywany w procesie palenia. Ognisko pożaru przemieszcza się w kierunku napływu świeżego powietrza, powiększając swoje wymiary zarówno wzdłuż, jak i w poprzek linii prądu. Z przeprowadzonych symulacji wynika, iż istnieje pewna graniczna wartość prędkości przepływu w zrobach, której przekroczenie powoduje gwałtowny rozwój ogniska pożaru. Stan ten charakteryzuje się zwiększeniem promienia bryły, z czym związane jest znaczne zwiększenie wydatku generowanych gazów pożarowych. Uzyskane na podstawie obliczeń rozmiary ogniska pożaru są rzędu kilku metrów, przy czym kształt bryły tworzącej ognisko pożaru przypomina odrywającą się kroplę wody.

Słowa kluczowe: wentylacja kopalń, pożar podziemny, symulacja komputerowa

1. Introduction

The mathematical simulation of the mine ventilation process in the presence of a fire located in a goaf necessitated the formulation of an appropriate mathematical model (Branny et. al 1995; Dziurzyński 1998). In the case under consideration it is assumed that a mixture of air and gases flows in a network of excavations, which are modelled as a set of one-dimensional air splits. The flow is analysed in the goaf, which is modelled as a two-dimensional area of the isotropic heterogenous porous medium. The network of excavations and the goaf have a common border, where the exchange of mass occurs.

The mathematical basis of the incompressible flow model in the network of excavations is a system of equations of continuity, status and movement, where the movement equation is analysed in the stationary state. To describe the flow in the goaf a system of equations of continuity, status and filtration according to Darcy's Law was used, whereas for the developing fire in the goaf, equations describing the exchange of heat by convection and conduction, including the heat emission resulting from the coal combustion, were introduced. Furthermore, the heat absorption by conduction into the goaf surrounding the fire was taken into account in the equation of temperature distribution in the fire.

This article outlines a mathematical model of the fire in the goaf together with boundary-initial conditions, the adopted numerical method and examples of simulation of development of the fire being considered in varying conditions of ventilation. Results of this simulation are presented graphically in time diagrams and in spatial distribution graphs.

2. The fire — its mathematical model

2.1. Simplifying assumptions

The present considerations are related to the area of a goaf of longwalls with backfill caving that is filled with rock waste and unextracted coal. It has been assumed that within the area of crushed coal in the goaf, conditions for spontaneous generation of heat occurred. The area in question is supplied with oxygen contained in a mixture of air and gases. The processes of oxidative self-heating of the coal and the build-up of heat result in an increase in temperature. When the flash-point is reached by a certain mass of coal, a process of intensive combustion (called "fire" for the purposes of this article) is initiated. The flow of the mixture of air and gases in the goaf takes place along the *stream-line* , this being the *directional line of gas-flow*, and is determined by the velocity vector $\bar{v}(v_x, v_y)$. Since the combustion of coal depends on the inflow of oxygen contained in the flowing mixture of gases, processes associated with the fire will be considered along the stream--line. The term "the fire" will be used herein to describe a certain separated porous area (Fig. 1), the temperature of which is higher than the so-called flash-point of coal. In the course of combustion, the dimensions of this area increase. We assume that the geometrical equivalent of the area in question is an axially symmetrical volume that

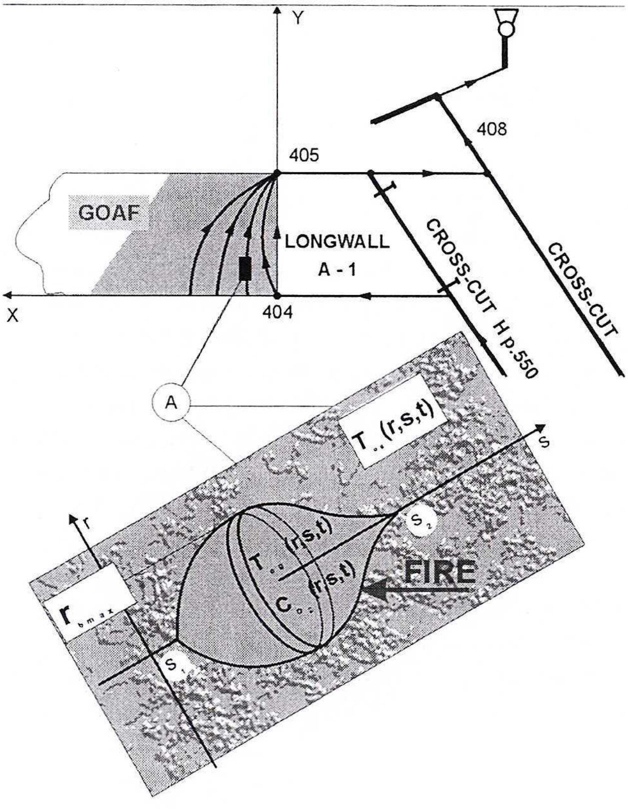


Fig. 1. Spatial diagram of wall area ventilation
A — fire diagram, where the following have been marked:
s — current coordinate, measured along the stream line, r — coordinate measured perpendicularly to the stream line, $r_{b\ max}$ — maximum radius of the fire, $T_{og}(r,s,t)$ — temperature of the fire, $T_z(r,s,t)$ — temperature of goaf, $C_{O_2}(r,s,t)$ — distribution of oxygen concentration in the mixture flowing into and through the fire

Rys. 1. Schemat przestrzenny przewietrzania rejonu ściany
A — schemat ogniska pożaru, gdzie oznaczono:
s — współrzędna bieżąca, mierzona wzdłuż linii prądu przepływu mieszaniny, r — współrzędna mierzona prostopadle do linii prądu, $r_{b\ max}$ — maksymalny promień ogniska pożaru, $T_{og}(r,s,t)$ — temperatura ogniska pożaru, $T_z(r,s,t)$ — temperatura zrobów, $C_{O_2}(r,s,t)$ — rozkład stężenia tlenu w mieszaninie przepływającej przez ognisko pożaru

increases its length and radius as the temperature of the fire rises. The longitudinal axis of this volume is the stream line, along which the flow of the mixture of air and gases takes place. When analysing the complicated process of mass energy exchange in the fire, the following phenomena are considered (Chomiak 1977; Wójcicki 1969):

- oxygen depletion resulting from the process of coal combustion; and the corresponding changes in oxygen concentration in the mixture of air as it flows through the area in which the fire is located,

- generation of combustion gases treated as a compound entity ($CO + CO_2 + C_nH_n + ...$),
- emission of heat as a result of the process of coal combustion in the fire,
- exchange of heat through convection and conduction in the fire,
- conductive collection of heat by the area not covered by combustion.

Fig. 1 shows a simplified diagram of the fire in a goaf adjacent to an active mining area fed by the ventilation network.

2.2. Oxygen consumption and generation of heat in the fire

As a result of the combustion process in the fire consumption of oxygen occurs, which determines the quantity of heat generated and the amount of combustion gases produced. To determine parameters in the equations that describe the combustion process, measurements obtained in real mining conditions were used. (Dziurzyński, Tracz 1994; Dziurzyński 1998).

Changes in oxygen concentration

It is assumed that the consumption of oxygen in the fire is determined by the intensity of the process of coal combustion, which is commonly known as the *unitary combustion rate*. Using the results of experimental research into the dynamics of the fire (Dziurzyński 1998), we assume that the rate of oxygen mass reduction relative to a given unit of volume is proportional to the quantity a_p and the concentration of oxygen, thereby obtaining:

$$k_{V,O_2} = \Psi a_p C_{O_2} \tag{2.1}$$

where:

k_{V,O_2} — rate of oxygen mass reduction [kg/m^{3}s],
$\Psi = \Psi[T_{og}(r,s,t)]$ — factor of proportionality [kg/m^{2}s],
a_p — combustion surface relative to one unit of volume [m^2/m^3],
$C_{O_2} = C_{O_2}(r,s,t)$ — distribution of oxygen concentration in the fire.

We shall determine the rate of coal combustion k_{vs} on the basis of the rate of oxygen mass reduction:

$$k_{vs} = \frac{a_p}{k_{O_2}} = \Psi C_{O_2} \tag{2.2}$$

where:

k_{O_2} — oxygen mass (kg) required for the combustion of 1 kg of coal (Chomiak 1997).

Changes in oxygen concentration in the flowing air and combustion gases through the fire are determined by the *equation of continuity*, expressed as follows:

$$m\frac{\partial \rho_{O_2}}{\partial t} + \frac{\partial(\rho_{O_2} v_p)}{\partial s} = -k_{v,O_2} \tag{2.3}$$

where:

t — co-ordinate of time,

ρ_{O_2} — partial oxygen density,

v_p — flow rate of the mixture of air and gases in the goaf,

m — porosity of the goaf at the site of the fire.

The mass concentration of oxygen in the mixture of air and combustion gases is expressed by the following dependence:

$$C_{O_2} = \frac{\rho_{O_2}}{\rho} \tag{2.4}$$

where:

ρ — density of the mixture of air and gases, e.g. combustion gases.

In accordance with the mass conservation law, for the mixture of air and combustion gases we have:

$$m\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_p)}{\partial s} = M_{ps} - k_{v,O_2} \tag{2.5}$$

where M_{ps} [kg/sm^3]is the increase in mass of the gaseous products of combustion, generated during the fire, accruing to a unit volume. We assume that in the case of coal combustion this increase is more or less equal to the quantity of fuel consumed. Knowing the unitary rate of combustion, which is expressed by dependence (2.2), we may write:

$$M_{ps} = k_{vs} \tag{2.6}$$

Taking into consideration formula (2.4) in equation (2.3), and also equation (2.5) and formula (2.6), the following expression can be obtained after transformations:

$$m\frac{\partial C_{O_2}}{\partial t} + v_p\frac{\partial C_{O_2}}{\partial s} = \frac{\Psi a_p}{\rho} C_{O_2}\left[1 + C_{O_2}\left(\frac{1}{k_{O_2}} - 1\right)\right] \tag{2.7}$$

Equation (2.7) serves to determine the distribution of oxygen concentration, this being one of the components of the flowing mixture, depending on oxygen mass consumption and the increase in the mass of the combustion gases.

The factor of proportionality Ψ was determined experimentally. In a function of the temperature of the fire, the factor of proportionality Ψ is determined by an empirical dependence obtained on the basis of a linear model (the correlation coefficient being equal to 0.95).

$$\Psi = -24.31 + 0.0357\ T_{og} \tag{2.8}$$

As a result of the fire experiments a dependence between A_w the heat exchange surface, which was called visible, and the value of the fire surface A_p was established. The best correlation of research results was obtained for a straight line passing through the centre of the coordinate system. The correlation coefficient equalled 0.84, and thus the following dependence was obtained jointly for the three experiments:

$$A_p = 110.94\, A_w \tag{2.9}$$

Data provided by further experiments (6) made it possible to assume that the process of combustion occurred within the entire thickness of the coal layer. Having accepted this assumption, it becomes possible to relate the combustion surface to the volume of the fire currently undergoing combustion. Therefore, dependence (2.9) may be transformed into the following form:

$$gr \cdot A_p = 110.94\, V_{og} \tag{2.10}$$

where:

$V_{og} = A_w \cdot gr$ — volume of the fire,
gr — thickness of the fire layer undergoing combustion.

By transforming dependence (2.10), the following is obtained:

$$a_p = \frac{A_p}{V_{og}} = \frac{110.94}{gr} \tag{2.11}$$

Heat emission

As a result of the combustion process, heat is generated within the fire. Heat generated in a unit of time and in a unit of volume is determined by applying the following formula:

$$q_w = k_{vs} W_d \tag{2.12}$$

where:

q_w — heat generated within the fire [J/sm^3],
W_d — calorific value of coal [J/kg].

By introducing dependences (2.1) and (2.2) into (2.12), we obtain the following:

$$q_w = \frac{a_p}{k_{O_2}} = \Psi C_{O_2} W_d \tag{2.13}$$

3. Changes in temperature of the fire

We will consider time-variable thermal processes which take place within the area that is occupied by the fire, taking into account heat conduction with simultaneous heat transfer. Let us determine the heat balance in the fire on the basis of an assumption that it is an isotropic porous medium. It comprises lumps of coal of differing sizes, between which the mixture of air and gases flows. A mathematical description of heat exchange and transport within the goaf is by no means simple, among other reasons due to the difficulty in determining the values of the physical parameters that serve to characterise the heat exchange between the flowing mixture of gases and the rubble which constitutes the goaf. It has been assumed that the fire is surrounded by a porous area that receives part of the heat generated in the fire. As far as heat exchange is concerned, the area in question is characterised by *substitute parameters* (Grochal 1994; Madejski 1963), such as:

- apparent density ρ_{pz} that may be determined using the equation:

$$\rho_{pz} = \rho_w(1 - m) + \rho m \tag{3.1}$$

where:

ρ_w — coal density, 1400 [kg/m^3],
ρ — density of the flowing mixture, e.g. 1.2 [kg/m^3].

Since the second component in relation (4.1) is considerably smaller than the first one, then — without any risk of making a significant error — we may accept that:

$$\rho_{pz} = \rho_w(1 - m) \tag{3.2}$$

The second parameter is the so-called *apparent thermal conductivity λ_p of the porous area*, which is connected with thermal conductivity λ_w of the core (i.e. coal) and thermal conductivity λ of the flowing mixture of air and gas. This interdependence is — among other factors — by the geometric arrangement of the lumps of coal, i.e. a factor additionally influencing permeability and porosity. The problem of determining the exact dependence between the above-mentioned quantities for a medium such as goaf remains, as yet, unsolved. Research conducted during the calculation of heat exchange in so-called "*packed deposits*" (Madejski J. 1963) indicates that the apparent conductivity of a medium without any flow occurring therein is lower than conductivity of the filling (i.e. coal). However, the value of apparent conductivity increases considerably when flow of the air mixture does occur. This is brought about by forced convection in the empty spaces of the porous medium. It may be assumed that apparent conductivity is a function of a number of parameters:

$$\lambda_p = \lambda_p(\lambda_w, \lambda, T, v_p, m, k, F_s \ldots) \tag{3.3}$$

where:

λ_w — thermal conductivity of coal, 0.186 [W/mK],
λ — thermal conductivity of the flowing mixture, e.g. for dry air $\lambda = 0.026$ [W/mK],
m, K, F_s — the porosity, permeability and specific surface, respectively; the specific surface is defined as the ratio between the surface area

of the lumps of coal constituting the filling (a core) and the total volume (the sum of volumes of both empty spaces and coal lumps),

$T,\ v_p$ — respectively, the temperature and velocity of the flowing mixture.

It follows from the above, that the determination of the value of apparent conductivity is by no means simple, and indeed requires special experimental research to be carried out. Another parameter that serves to characterise the vicinity of the fire is specific heat. The values of specific heat for coal and air are of the same order. Therefore, for the purposes of further considerations it has been assumed that the area under consideration is represented by the specific heat of coal (Branny et al. 1995).

The equation used to calculate changes of the temperature of the fire is determined on the basis of thermal balance, considered both for the mixture of air and gases flowing through empty spaces (pores), as well as for the coal constituting the core of the fire. We will consider the flow of the mixture of air and gases solely along the axis of the mass of coal. When arranging the balance, we will additionally assume that the temperature of the mixture flowing through the empty spaces and the temperature of the coal undergoing combustion are identical and equal to the temperature of the fire itself. Taking the above into consideration, the thermal balance for the fire, which is an axially symmetrical mass of coal, comprises the following components:

- internal energy, contained in the mixture of air and gases that flows through the empty spaces of the porous medium in a unit of time and volume:

$$q_1 = c_p \rho \left(\frac{\partial T_{og}}{\partial t} + v_p \frac{\partial T_{og}}{\partial t} \right) \tag{3.4}$$

- heat contained in the core, as related to a unit of time and volume during a change in the temperature of the fire:

$$q_2 = c_w \rho_w (1-m) \frac{\partial T_{og}}{\partial t} \tag{3.5}$$

- heat conducted within the fire, referring to a unit of time and volume:

$$q_3 = \lambda_{pog} \left(\frac{1}{r} \frac{\partial T_{og}}{\partial r} + \frac{\partial^2 T_{og}}{\partial r^2} + \frac{\partial^2 T_{og}}{\partial s^2} \right) \tag{3.6}$$

- heat emitted by the coal undergoing combustion within the fire, as related to a unit of time and volume, determined by formula (3.2):

$$q_4 = q_w \tag{3.7}$$

where:

c_w — specific heat of coal, $c_w = 1.3$ [kJ/kgK],

c_p — specific heat of the flowing mixture, $c_p = 1.0$ [kJ/kgK],

λ_{pog} — apparent conductivity of the fire.

Effecting the balance for various components (3.4), (3.5), (3.6), (3.7), after a number of transformations we obtain an equation similar to Kirchhoff-Fourier's equation, (Staniszewski 1979), which describes the distribution of the temperature within the fire:

$$[c_w\rho_w(1-m)+c_p\rho]\frac{\partial T_{og}}{\partial t}+c_p\rho v_p\frac{\partial T_{og}}{\partial s}\lambda_{pog}\left[\frac{1}{r}\frac{\partial T_{og}}{\partial r}+\frac{\partial^2 T_{og}}{\partial r^2}+\frac{\partial^2 T_{og}}{\partial s^2}\right]+q_w \tag{3.8}$$

3.1. Collection of heat by surrounding goaf

The heat exchange between the fire and the remaining part, i.e. that not covered by combustion, takes place solely through conductivity. Taking into account the heating of the area that includes the fire, it has been assumed that the movement of heat within the surrounding area is described by an equation of conductivity. Presented in cylindrical coordinates and under the assumption of axial symmetry of the temperature distribution it can be expressed as follows (Staniszewski 1979; Madejski 1977):

$$\frac{\partial T_z(r,s,t)}{\partial t}=\frac{\lambda_{pzr}}{\rho_{pz}c_w}\left[\frac{1}{r}\frac{\partial T_z}{\partial r}+\frac{\partial^2 T_z}{\partial r^2}+\frac{\partial^2 T_z}{\partial s^2}\right] \tag{3.9}$$

where:

λ_{pzr} — apparent conductivity of goaf (area surrounding the fire),
$T_z = T_z(r,s,t)$ — distribution of temperature within the area of goaf surrounding the fire.

4. Boundary and initial conditions

The solution of the mathematical relations describing physical phenomena during a fire in a goaf presented above requires supplementation with information concerning boundary-initial conditions. We will determine them for the following equations:

- fluctuations of the oxygen concentration C_{O_2} in the mixture of the air flowing through the fire; equation (2.8),
- fluctuations of the fire temperature T_{og}; equation (3.8),
- fluctuations of temperature in the area surrounding the fire T_z; equation (3.9).

According to the assumption made, the fire is a solid form having axial symmetry. The axis of symmetry is tangential to the line of the flow-stream in goaf in the site of the fire's origin. The area limiting the fire is expressed by the following function:

$$r_b = f_b(s,t) \qquad s\in[s_1(t),s_2(t)] \tag{4.1}$$

where:

$s_1(t), s_2(t)$ — netutral points of the function $f_b(s,t)$.

Additionally, it is assumed that the function $f_b(s,t)$ has in its determination range one maximum value at the point $s_{m(t)}$ and its value at this point is $r_{b\max}(t)$. This function specifies the fire-goaf boundary for the system of equations of the temperature distribution and oxygen concentration distribution in the fire and the temperature distribution in the goaf.

At the initial moment $t = 0$ the self-ignition of coal starts in the solid limited by the area determined by the function $t_{b0} = f_b(s,0)$, where we assume that the temperature T_{z0} in this volume increases in a linear manner in time $t \in [0, t_0]$:

$$T_{z0}(t) = \frac{T_{zw} - T_w}{t_0} t + T_w \tag{4.2}$$

where:

- T_{zw} — coal ignition temperature,
- T_w — initial temperature,
- t_0 — the starting moment of the coal combustion process in the fire.

At moment t_0 the temperature distribution T_z in goaf is described by equation (3.9) with the following boundary and initial conditions.

Boundary conditions:

- the fire-goaf boundary

$$T_z(r_{b0}, s, t) = T_{z0}(t) \qquad \text{for} \qquad s \in [s_1(0), s_2(0)] \tag{4.3}$$

- the external boundary

$$\begin{aligned} T_z(r_\infty, s, t) &= T_w && \text{for} && s \in [-s_\infty, s_\infty] \\ T_z(r, -s_\infty, t) &= T_w && \text{for} && s \in [0, r_\infty] \\ T_z(r, +s_\infty, t) &= T_w && \text{for} && r \in [0, r_\infty] \end{aligned} \tag{4.4}$$

where:

- r_∞ — distance in the direction of the coordinate r, where it can be assumed that $T_z = T_w$,
- s_∞ — distance in the direction of the coordinate s, where it can be assumed that $T_z = T_w$.

Initial conditions:

$$T_z(r, s, 0) = T_w \qquad \text{for} \qquad r \in [0, r_\infty] \qquad \text{and} \qquad s \in [-s_\infty, s_\infty] \tag{4.5}$$

From the moment t_0 (start of the fire) the distribution of temperature is described by equation (3.8). For this equation the following boundary and initial conditions are assumed:

Boundary conditions for the fire-goaf boundary:

$$\lambda_{pog} \left. \frac{\partial T_{og}}{\partial r} \right|_{r_b,s,t} = \lambda_{pzr} \left. \frac{\partial T_z}{\partial r} \right|_{r_b,s,t} \tag{4.6}$$

$$\lambda_{pog} \left. \frac{\partial T_{og}}{\partial s} \right|_{r_b,s,t} = \lambda_{pzr} \left. \frac{\partial T_z}{\partial s} \right|_{r_b,s,t} \qquad \text{for} \qquad s \in [s_1(t), s_2(t)]$$

where the function describing the boundary $r_b = f_b(s,t)$ meets the following conditions:

$$T_{og}(r_b,s,t) = T_z(r_b,s,t) = T_{zw} \tag{4.7}$$

Initial condition for the equation (3.8) :

$$T_{og}(r,s,t_0) = T_{zw} \qquad \text{for} \quad r \le f_b(s,t) \quad \text{and} \quad s \in [s_1(t_0), s_2(t_0)] \tag{4.8}$$

$$\left. \frac{\partial T_{og}}{\partial r} \right|_{r_b,s,t_0} = \left. \frac{\partial T_z}{\partial r} \right|_{r_b,s,t_0} \qquad \text{for} \quad s \in [s_1(t_0), s_2(t_0)]$$

$$\left. \frac{\partial T_{og}}{\partial s} \right|_{r_b,s,t_0} = \left. \frac{\partial T_z}{\partial s} \right|_{r_b,s,t_0} \qquad \text{for} \quad s \in [s_1(t_0), s_2(t_0)]$$

where:

$s_1(t_0) = s_1(0)$ and $s_2(t_0) = s_2(0)$

Initial conditions of derivatives $\frac{\partial T_{og}}{\partial r}$ and $\frac{\partial T_{og}}{\partial s}$ at the fire boundary are obtained from the calculated temperature distribution T_z in the goaf at the moment t_0. The distribution $T_z(r,s,0)$ is at the same time the initial distribution in further computation of the temperature distribution in the goaf for $t > t_0$ and for boundary conditions (4.4), (4.8), (4.7).

For equation (2.8), that describes changes in the oxygen concentration, it is assumed that the direction and sense of the air velocity is identical with the direction and sense of the s coordinate axis and the following boundary condition is assumed:

$$C_{O_2}(r_b,s,t) = C_{O_2} \qquad \text{for} \qquad s \in [s_1(t), s_m(t)] \tag{4.9}$$

where:

- $s_m(t)$ — the coordinate of a point where the function $r_b = f_b(s,t)$ reaches its maximum,
- C_{O_2} — the oxygen concentration in the mixture flowing to the fire.

The initial condition for equation (2.8):

$$C_{O_2}(r_b, s, t_0) = C_{O_2} \qquad \text{for} \qquad s \in [s_1(t_0), s_2(t_0)] \tag{4.10}$$

5. Numerical method

The aforementioned differential equations of the mathematical model of the fire describe responses of some goaf during the coal combustion process. Therefore, it is necessary to obtain results for subsequent moments.

Changes in the oxygen concentration $C_{O_2}(r,s,t)$ are determined by the equation of transport in the porous medium (2.7). Because of the relationship $\Psi = \Psi[T_{og}(r,s,t)]$ equation (2.8) is solved with the use of the "r" coordinate. To obtain the result, the approximation method of derivatives by the following differential model was used (Kalitkin H.H. 1978):

$$m\frac{C^{v+1}_{O_2,i+1,j} - C^{v}_{O_2,i+1,j}}{\Delta t} + v^{v}_{p,j}\frac{C^{v+1}_{O_2,i+1,j} - C^{v+1}_{O_2,i,j}}{\Delta s} = \tag{5.1}$$

$$= \frac{a_p \Psi^{v}_{i,j}}{\rho^{v}_{i,j}} C^{v}_{O_2,i,j}\left[1 + C^{v}_{O_2,i,j}\left(\frac{1}{k_{O_2}} - 1\right)\right]$$

After appropriate transformations of the differential equation (5.1), the following may be developed:

$$C^{v+1}_{O_2,i+1,j} = \frac{1}{1+W^{v}}\left\{C^{v}_{O_2,i+1,j} + W^{v}C^{v+1}_{O_2,i,j} + W_1^{v}C^{v}_{O_2,i,j}\left[1 + C^{v}_{O_2,i,j}\left(\frac{1}{k_{O_2}} - 1\right)\right]\right\} \tag{5.2}$$

where:

$$W^{v} = \frac{\Delta t}{m\Delta s} v^{v}_{p,j} \tag{5.3}$$

$$W_1^{v} = \frac{\Delta t a_p \Psi^{v}_{i,j}}{m\rho^{v}_{i,j}} \tag{5.4}$$

v — next time step,
Δt — the interval of a time step,
Δs — length of a spatial step in the direction of the "s" coordinate; $-s_\infty \le s \le +s_\infty$,
i — i-th row, $i = 0, 1, 2, \ldots I$,
j — j-th column, $j = 0, 1, 2, \ldots J$.

The differential equation (5.2) corresponds with the equation (2.8) and determines the oxygen concentration level at the next moment for $i+1, j$ spatial point along the "s" and "r" coordinates.

Changes in the fire temperature $T_{og}(r,s,t)$ are determined by the equation of transport and heat conductivity in the porous medium (3.8). To obtain the solution, the approximation method by the overt differential model in the rectangular grid was used:

$$A_1 \frac{T^{v+1}_{og,i,j} - T^{v}_{og,i,j}}{\Delta t} + A_2 v^v_p \frac{T^{v}_{og,i+1,j} - T^{v}_{og,i-1,j}}{2\Delta s} = \tag{5.5}$$

$$= \lambda_{pog} \frac{T^{v}_{og,i+1,j} - 2T^{v}_{og,i,j} + T^{v}_{og,i-1,j}}{\Delta s^2} + \lambda_{pog} \frac{T^{v}_{og,i,j+1} - T^{v}_{og,i,j-1} + T^{v}_{og,i-1,j}}{2r\Delta r} +$$

$$+ \lambda_{pog} \frac{T^{v}_{og,i,j+1} - 2T^{v}_{og,i,j} + T^{v}_{og,i-1,j}}{\Delta r^2} + q^v_{w,i}$$

where:

$A_1 = [c_w \rho_w (1-m) + c_p \rho]$

$A_2 = c_p \rho$,

Δr — length of a spatial step in the direction of the "r" coordinate, $0 \le r \le r_\infty$

Δs — length of a spatial step in the direction of the "s" coordinate,

i — i-th row, $i = 0, 1, 2, \dots I$,

j — j-th column, $j = 0, 1, 2, \dots J$.

In our further considerations a uniform division in the direction of "r" and "s" coordinates is assumed. Thus, we obtain $\Delta r = \Delta s = h$ and $r = (j-1)h$. After appropriate transformations of the differential equation (5.5) we obtain the following equation:

$$T^{v+1}_{og,i,j} = T^{v}_{og,i,j} + \frac{\lambda_{pog} \Delta t}{A_1 h^2} \left\{ T^{v}_{og,i+1,j} - 4T^{v}_{og,i,j} + T^{v}_{og,i-1,j} - \frac{A_2 h v^v_p}{2\lambda_{pog}} \cdot \right. \tag{5.6}$$

$$\left. \cdot (T^{v}_{og,i+1,j} - T^{v}_{og,i-1,j}) - \frac{T^{v}_{og,i,j+1} - T^{v}_{og,i,j-1}}{2(j-1)} + T^{v}_{og,i,j+1} - T^{v}_{og,i,j-1} \right\} + \frac{\Delta t}{A_1} q^v_{w,i,j}$$

This differential equation is valid for all points in the grid, with exception of points on the axis for $r = 0$, i.e. $j = 1$. For $r = 0$ a singularity is present, which will be eliminated in the following way:

- for $r \to 0$ it is:

$$\lim_{r \to 0} \frac{1}{r} \frac{\partial^2 T_{og}}{\partial r^2} = \frac{\partial^2 T_{og}}{\partial r^2} \tag{5.7}$$

Taking into consideration the condition (5.7) in the equation (3.8), and then in the differential equation, after transformations we obtain the following:

- for r = 0, it is:

$$T^{v+1}_{og,i,j} = T^{v}_{og,i,1} + \frac{\lambda_{pog}\Delta t}{A_1 h^2}\left\{T^{v}_{og,i+1,1} - 2T^{v}_{og,i,1} + T^{v}_{og,i-1,1} - \frac{A_2 h v^{v}_{p}}{2\lambda_{pog}}\cdot\right. \tag{5.8}$$

$$\left.\cdot(T^{v}_{og,i+1,1} - T^{v}_{og,i-1,1}) + 2(T^{v}_{og,i,2} - 2T^{v}_{og,i,2} + T^{v}_{og,i,0})\right\} + \frac{\Delta t}{A_1} q^{v}_{w,i,1}$$

The differential equations (5.6) and (5.8) correspond with equation (3.8) and describe values of the fire temperature at the next moment $v+1$, for i,j spatial point, where the solution is known for the entire area of calculations for the v-th time step.

Temperature changes in the area surrounding the fire $T_z(r,s,t)$ are described by the heat conductivity equation (3.9). The solution of this equation was obtained by approximation in the overt model on the basis of a rectangular grid, for which we assume a uniform division of space in the direction of "r" and "s" coordinates, obtaining as follows:

$$\frac{T^{v+1}_{z,i,j} - T^{v}_{z,i,j}}{\Delta t} = \frac{\lambda_{pzr}}{\rho_{pz} c_w}\cdot \tag{5.9}$$

$$\cdot\left[\frac{T^{v}_{z,i,j+1} - 2T^{v}_{z,i,j} + T^{v}_{z,i,j-1}}{\Delta r^2} + \frac{T^{v}_{z,i,j+1} - T^{v}_{z,i,j-1}}{2r\Delta r} + \frac{T^{v}_{z,i+1,j} - 2T^{v}_{z,i,j} + T^{v}_{z,i-1,j}}{\Delta s^2}\right]$$

After appropriate transformations of the differential equation (5.9), taking into account that $\Delta r = \Delta s = h$ and $r = (j-1)h$, we obtain the following:

$$T^{v+1}_{z,i,1} = T^{v}_{z,i,1} + A_3\cdot \tag{5.10}$$

$$\cdot\left[T^{v}_{z,i,j+1} - 4T^{v}_{z,i,j} + T^{v}_{z,i,j-1} + \frac{1}{2(j-1)}(T^{v}_{z,i,j+1} - T^{v}_{z,i,j-1}) + T^{v}_{z,i+1,j} + T^{v}_{z,i-1,j}\right]$$

where:

$A_3 = \dfrac{\lambda_{pzr}}{\rho_{pz} c_w}\dfrac{\Delta t}{h^2}$, whereas other symbols are as in the equation (5.6).

The above-presented equation is valid for all points of the grid, with exception of points on the axis for $r = 0$, i.e. $j = 1$. For $r = 0$ a singularity is present, which will be eliminated using the condition (5.7). Including the condition (5.7) in the equation (3.9), and then in the differential equation, the following result will be obtained after transformations:

- for $r = 0$:

$$T^{\nu+1}_{z,i,1} = T^{\nu}_{z,i,1} + A_3[2T^{\nu}_{z,i,2} - 6T^{\nu}_{z,i,1} + 2T^{\nu}_{z,i,0} + T^{\nu}_{z,i+1,1} + T^{\nu}_{z,i-1,1}] \tag{5.11}$$

The differential equations (5.10) and (5.11) correspond with the equation (3.9) and describe the value of temperature in the area of goaf surrounding the fire at the next moment $\nu+1$, for the spatial point i,j, where the solution is known for the entire area of computation for the ν-th time step.

The numerical method used for the presented system of equations is based on the overt numerical model, for which it is difficult to specify conditions of stability because of lack of experimental data that correspond with the presented system of equations.

In the process of calculations, it was endeavoured to adjust the time and spatial steps so as not to allow for the oscillation of the solution. The generation of oscillations leads to serious errors and, in consequence, to the instability of the solution. Obviously, it is possible to use other, more effective, numerical methods to obtain the solution, such as the alternate directions method. Using the aforementioned numerical method, results were obtained, which allow for the identification of qualitative temperature changes in the fire located in the goaf under consideration.

6. Determination of the temperature distribution in the fire — the computer simulation

The issue of mutual interactions between the ventilation network and the goaf necessitates solving equations that describe responses of both the goaf and the ventilation network. According to the mathematical model adopted (Dziurzyński 1998) and appropriate boundary and initial conditions, a computer simulation model was developed with the following features:

- it uses a database created by VENTGRAPH Ventilation Engineer's System software (Dziurzyński 1993);
- it allows for easy preparation and entry of data for multi-optional examples;
- interactive software interface;
- graphic presentation of computed results directly on the computer screen with the use of the spatial diagram of the mine ventilation network, using procedures of visualisation of currently calculated results related to nodes and ventilation air splits, such as pressure, flow rate, velocity, pressure loss, as well as the application of procedures of plotting isopleths of pressure levels in the goaf, isopleths of concentration levels of a selected component of gases, which are transported in the area of the goaf.

Resulting drawings of isopleths are mapped directly on the spatial diagram in accordance with their physical location in the goaf. It enables us to observe changes in concentration and pressure distribution in real time of computation. Furthermore, it is possible to record currently computed results at any time in a form of a set of data, which allows for the calculated results to be presented.

Thanks to the use of this simulation software, it is possible to determine the following parameters for the ventilation network and the goaf:

- air distribution in the ventilation network with the vector of the flow rate in air splits of the network,
- distribution of concentrations and densities in air splits of the ventilation network,
- distribution of pressure, velocity, concentration and density in the goaf by computing a two-dimensional system of equations of temperature distribution in the fire and the area of goaf in its immediate vicinity.

To present effects of varying conditions of the flow on the distribution of air and combustion gases in the goaf during the fire, calculations for two different systems of ventilation were performed:

- U-type ventilation system; exploitation from boundaries — example I,
- U-type ventilation system; exploitation to boundaries — example II.

In all examples of calculations it was assumed that the air flow in the goaf is disturbed by the fire within the goaf. In individual examples of fire situations, modifications of the flow conditions were made, which included:

- constructing ventilation fire dams,
- opening existing fire dams.

The objective of the simulation of changes in conditions of the flow of air and gases in the network of excavations and the goaf is to forecast the process of ventilation in a goaf disturbed by a fire. The identification of the distribution of combustion gases generated in the fire, goaf and wall excavations will allow for obtaining characteristic situations for given locations of the a fire and a ventilation fire dam.

6.1. Example I — U-type ventilation system; exploitation from boundaries

As an example for research the Z mine region was selected. The following parameters were used in the calculations:

- deposit of coal was located horizontally, the calorific value of the coal — 4200 kcal,
- exploitation of a longwall with backfill caving, exploitation from boundaries,
- U-type ventilation system,
- wall length of 130 m, the analysed wall projection of 100 m,
- volumetric concentration of oxygen at the exposed face of the wall — 20%.
- heat conductivity coefficient of goaf λ_{pzr} = 0.07 [W/mK],
- heat conductivity coefficient of the fire λ_{pog} = 0.04 [W/mK],
- air temperature at the exposed face of the wall T_w = 295 [K].

It was assumed that the fire is located in the goaf. The fire coordinates (Fig. 1) are as follows: x = 25 metres and y = 40 metres. Data related to parameters of the network of excavations were obtained from ventilation measurements carried out in real conditions in the Z mine. The following situations were analysed:

A — unrestricted flow,

B — restricted flow, — a local increase of resistance at the beginning of the wall [y = 20 m], the fire located in the goaf,

A — unrestricted flow

Fig. 2 presents the spatial diagram of the region under consideration, including results of calculations after 10 hours from the outbreak of the fire. The air flow rate through the wall was 26 m^3/s. In the case analysed the air flow velocity through the fire was 14 mm/s. Fig. 2 is a copy of the situation displayed on the computer screen during the computation. It visualises:

- isopleths of concentration levels of combustion gases for the goaf area,
- distribution of concentration levels of combustion gases (the thick line) in wall excavations.

Another method of presenting the obtained solution is the spatial diagram of a selected parameter, such as the distribution of concentration levels of combustion gases in the goaf.

Fig. 3 presents distribution of concentrations of combustion levels, whereas Fig. 4 shows the distribution of the modulus of flow velocity in the goaf. As shown, combustion gases are released in the upper section of the wall and mix with the air flowing through the wall, thus reducing the concentration of individual components of the mixture.

Fig. 4 presents distribution of the modulus of the mixture flow velocity in the goaf. The solution indicates that the highest velocity in the goaf occurs next to the upper corner of the wall. Furthermore, a fast reduction of the flow velocity of the mixture is observed in the goaf for a given ventilation system.

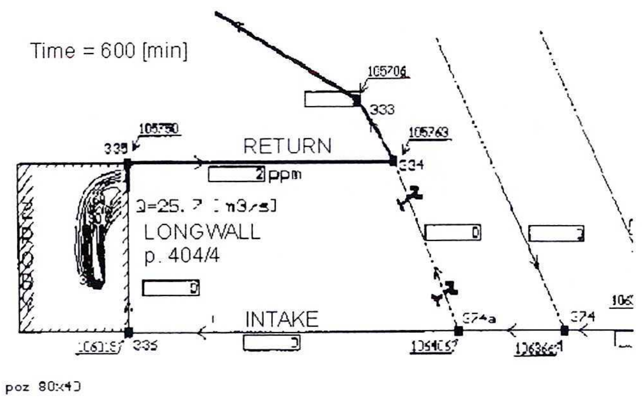


Fig. 2. Spatial diagram of the network of excavations — computer simulation — fire in goaf, isopleths of concentration levels of combustion gases

Rys. 2. Schemat przestrzenny sieci wyrobisk — symulacja komputerowa — pożar w zrobach, izolinie stężeń gazów pożarowych

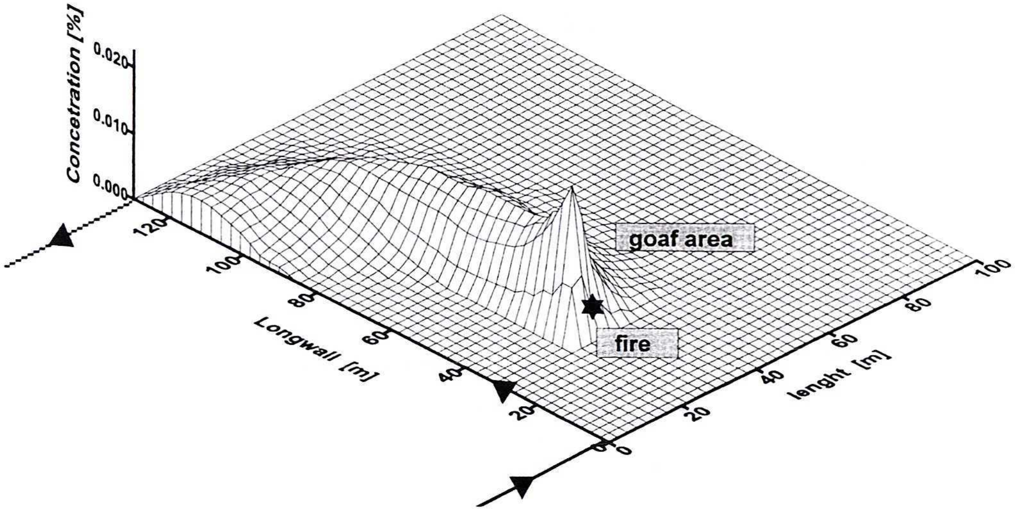


Fig. 3. Distribution of concentration levels of combustion gases in goaf — computer simulation

Rys. 3. Rozkład stężenia gazów pożarowych w zrobach — symulacja komputerowa

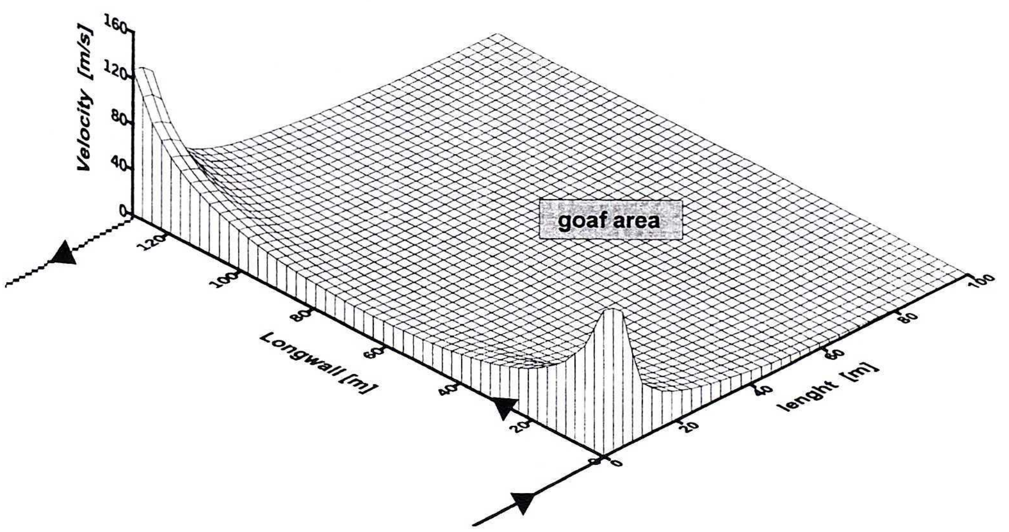


Fig. 4. Distribution of the modulus of flow velocity in goaf — example A — computer simulation

Rys. 4. Rozkład modułu prędkości przepływu w zrobach — przykład A — symulacja komputerowa

Fig. 5 presents solutions concerning the fire as described by the system of equations (2.7), (3.8) and (3.9). The temperature distribution was chosen as the means of presentation of the status of the fire, which is shown in this figure as isopleths 350 and 700 K. The 700 K isopleth is a conventional boundary between the fire and

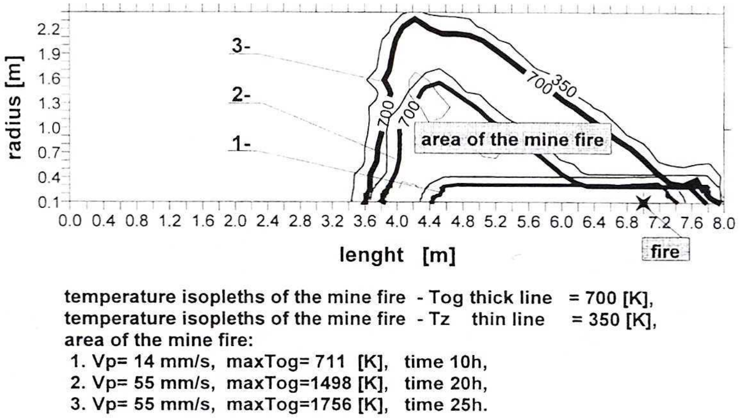


Fig. 5. Temperature isopleths of the fire — computer simulation

Rys. 5. Izolinie temperatury ogniska pożaru — symulacja komputerowa

the surrounding goaf and reflects the current shape of the fire. It can be said that from the 700 K isopleth (i.e. above the coal flash-point temperature) the solid shape created in this way forms the delineates and encloses fire. Inside the fire the temperature rises and it is in this area that the combustion process takes place. The presence of high temperature alone is not sufficient for the combustion process to occur, as it also requires oxygen, which is present in the flowing mixture of gases. Distribution of temperature isopleths for selected time moments is presented in the system of coordinates under consideration (length and radius of the fire).

Fig. 5 presents 700 K isopleths of the fire, which reflect its development in time in conditions of the example considered. In this example, where the flow is unrestricted, the fire's solid shape resembles a cylinder; this situation is represented by the isopleth designated as no.1. Situations represented by isopleths no 2 and 3 relate to example B, where the flow through the wall was restricted. This condition was achieved by simulation of an increase in the local resistance at the lower section of the wall. It resulted in a local increase of the air flow velocity through the goaf and rapid development of the fire. Presented isopleths 700 K reflect various possible shapes of the fire. This shape is determined, among other factors, by the value of the air flow velocity and the duration of the combustion process.

B — restricted flow — a local increase of resistance at the beginning of the wall

This example was to determine changes in the fire and its development as well as modifications in the distribution of combustion gases concentrations in the goaf and wall excavations compared with the initial status (example A). The air flow rate through the wall was limited $Q = 17.5\ m^3/s$.

Fig. 6 presents the solution obtained after 12 hours from the moment of constructing a dam. A characteristic earlier outflow of combustion gases is visible along half of its length in comparison with the initial status presented in Fig. 2.

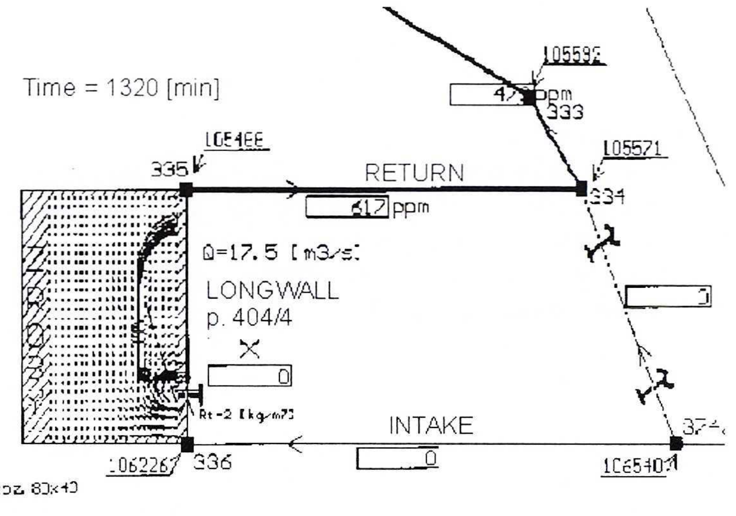


Fig. 6. Spatial diagram of the network of excavations — computer simulation, the fire in goaf (isopleths of combustion gases concentration levels, lines of stream for the flow in goaf)

Rys. 6. Schemat przestrzenny sieci wyrobisk — symulacja komputerowa, pożar w zrobach (izolinie stężeń gazów pożarowych, linie prądu dla przepływu w zrobach)

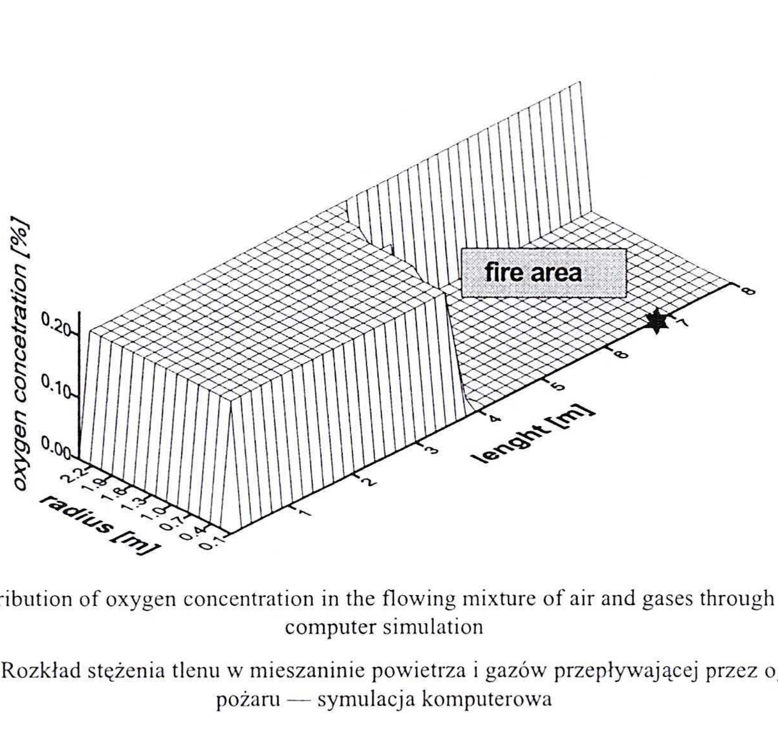


Fig. 7. Distribution of oxygen concentration in the flowing mixture of air and gases through the fire — computer simulation

Rys. 7. Rozkład stężenia tlenu w mieszaninie powietrza i gazów przepływającej przez ognisko pożaru — symulacja komputerowa

Another effect of the local increase of resistance is a sudden growth of the fire, which is reflected in the increased stream of generated combustion gases up to the value of 0.08 m^3/s. Thus, the concentration of carbon monoxide in air measured at the outlet from the wall increased significantly more than what would be expected on the basis of the decreased flow through the wall (Fig. 6). Development of the fire is caused by an increased inflow of fresh air flow to the fire. In the location of the fire an increase in the flow velocity up to 55 mm/s occurred. This situation can be observed in Fig. 6, where presented lines of stream have a length proportional to the value of the flow velocity. The increase of velocity leads to an increase of dimensions of the fire, which is shown by isopleths no 2 and 3 presented in Fig. 5.

In addition, Fig. 7 presents a spatial distribution of oxygen concentration in the flowing mixture of air and gases through the area of goaf, where the fire is located.

It is also a result of the solution of the equation 2.7. The distribution of the oxygen concentration presented reflects the oxygen consumption in the coal combustion process. A sudden decline of the oxygen content is apparent, which suggests that the combustion process occurs in this area, where oxygen is present. The fire moves forwards and against the stream. A slight backward movement of the zone of the fire is also observed. (Fig. 5).

6.2. Example II — U-type ventilation system; exploitation to boundaries

As an example for our analysis, a region of the wall exploited to boundaries in the U-type ventilation system was selected. Fig. 8 presents the spatial diagram of this region. Data related to parameters of excavations were obtained from ventilation measurements performed in real conditions in the P mine. A fire develops in a goaf. Coordinates of the fire are as follows: $x = 95$ m, $y = 60$ m.

In the example II effects of the opening of the dam in excavation 2–9, the inclined drift H-3, were analysed. This manoeuvre resulted in an increased flow rate in the inclined drift H-3 and a decreased flow rate in wall excavations and a decline in the flow of the mixture of air and combustion gases in the goaf. In the vicinity of the fire the flow velocity fell from 26 mm/s to 6 mm/s. Despite the reduced velocity the flow rate of generated combustion gases increased up to 0.025 m^3/s (Fig. 10). It was caused by further development of the fire in spite of limited air flow. This situation is illustrated in Fig. 9 (curves 2 and 3). Isopleths 700 K presented in Fig. 9 show development of the fire and changes in its shape during the next time intervals. The reduction of the flow velocity did not result in a reduction of the combustion processes in the fire within the time span analysed (24 hours).

Fig. 10 presents changes of the generated flow rate of combustion gases in the fire in time. The opening of a dam in the inclined drift caused a temporary decline of the flow rate of generated gases, after which further development of the fire continued with further increase of the flow rate of generated combustion gases.

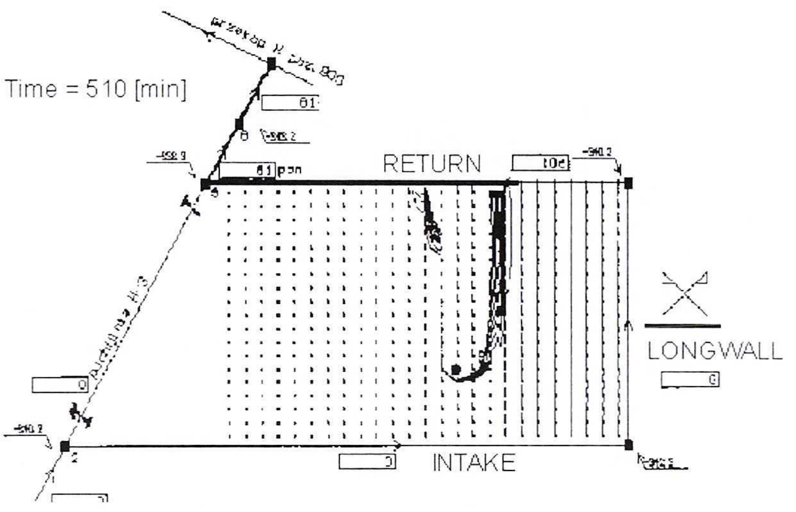
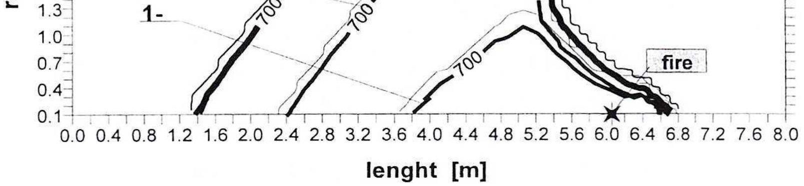


Fig. 8. Spatial diagram of the network of excavations — computer simulation, fire in goaf (isopleths of combustion gases concentration levels, lines of stream for the flow in goaf)

Rys. 8. Schemat przestrzenny sieci wyrobisk — symulacja komputerowa, pożar w zrobach (izolinie stężeń gazów pożarowych, linie prądu dla przepływu w zrobach)



temperature isopleths of the mine fire - Tog thick line = 700 [K],
temperature isopleths of the mine fire - Tz thin line = 350 [K],
area of the mine fire:
1. Vp= 26 mm/s, maxTog=1356 [K], time 10h,
2. Vp= 6 mm/s, maxTog=1650 [K], time 20h,
3. Vp= 6 mm/s, maxTog=1778 [K], time 24h.

Fig. 9. Temperature isopleths of the fire, example II

Rys. 9. Izolinie temperatury ogniska pożaru, przykład II

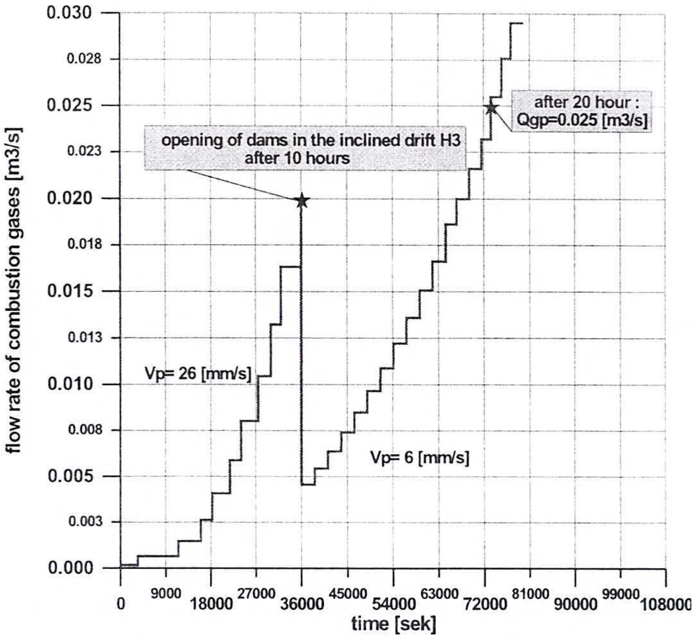


Fig. 10. Flow rate of combustion gases generated in the fire

Rys. 10. Wydatek generowanych gazów pożarowych w ognisku pożaru

7. Conclusions

The solutions for the fire presented above give a general picture of development of a fire located in a goaf. This paper discussed spatial and time temperature distribution of the fire and the surrounding goaf for various ventilation conditions.

The combustion process occurs in the fire mainly at the contact-region of its face with the inflowing air. As a result of low flow velocities in the goaf (several mm/s), oxygen is consumed fast by the combustion process. The fire moves in the direction of the fresh air inflow, increasing its size both along and across the line of stream. The simulations performed indicate that there is a certain border value of the flow velocity in the goaf, exceeding which leads to sudden development of the fire. This condition is characterised by an increased radius of the solid, with a significantly higher flow rate of generated combustion gases. The calculated size of the fire is several metres and the shape of the solid that forms the fire resembles a falling drop of water.

In this article two new directions of research were indicated. It is necessary to continue development of measurement methods of parameters that determine the air-flow in the mine ventilation network, and in its goaf in particular. At present such improvement is possible. Advancements in the design of sensors for measurement of air flow pressure or velocity will probably lead to innovation in the field of modern measuring and recording equipment. This equipment will enable us to carry out many more experiments. The objective of these experiments will be to verify parameters of the mathematical models used. It applies in particular to such parameters as apparent permeability or conductivity of goaf. It will lead to development of a method of forecasting potential locations of fires in goafs or in other parts of coal-mine exca- vations.

In Chapters 2 and 3 of this article materials from the paper (Dziurzyński 2000) with minor modifications were used.

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