JANUSZ CYGANKIEWICZ*

DETERMINATION OF CRITICAL CONDITIONS OF SPONTANEOUS COMBUSTION OF COAL IN LONGWALL GOB AREAS

WYZNACZANIE WARUNKÓW KRYTYCZNYCH SAMOZAPALANIA WĘGLA W ZROBACH ŚCIAN

Decades of experience in the fight against endogenous fire hazard in coal mines indicate a major influence of certain conditions in a given area of the mine on the possibility of fire occurrence, such as:

susceptibility of coals to spontaneous combustion,

oxygen content in the air incoming to the self-heating coal,

conditions of heat exchange between the self-heating coal mass and the environment

This paper presents a numerical method for determining the critical conditions of spontaneous combustion of coal in longwall gob areas, i.e. conditions under which spontaneous combustion may occur. It has been assumed that crushed coal in the gob has a shape of a flat layer adjacent from the roof and floor side to the rocks.

Our considerations have been limited to coals containing small amount of moisture. A simple model of oxidation kinetics on the coal surface expressed by the Arrhenius equation has been adopted. This model assumes that oxidation rate is independent of the amount of oxygen absorbed by coal. The rate of reaction depends only on temperature, with the parameters of the equation changing after the coal has reached the critical temperature.

The article presents also a mathematical model of spontaneous heating of the coal layer in the gob area. It describes the heat balance in the coal as well as the oxygen and heat balance in the flowing gases. The model consists of a system of differential equations which are solved using numerical techniques. The developed computer program enables to perform the relevant calculations.

In this paper, on the example of coal from a seam 405, we present the method for determining the following critical parameters of the layer of crushed coal: thickness of the layer, oxygen content in a stream of gases flowing through the layer and thermal conductivity of surrounding rocks.

Keywords: spontaneous combustion, coal, mathematical model, numerical solutions, critical conditions of spontaneous combustion

*   CENTRAL MINING INSTITUTE, PLAC GWARKÓW 1, 40-166 KATOWICE, POLAND

762

Wieloletnie doświadczenie w zakresie zwalczania zagrożenia pożarem endogenicznym w kopalniach wskazują na zasadniczy wpływ na możliwość zaistnienia pożaru niektórych warunków panujących w danym miejscu kopalni, takich jak:

- skłonność węgla do samozapalania

- zawartość tlenu w powietrzu dopływającym do zagrzewającego się węgla.

W pracy przedstawiono numeryczną metodę wyznaczania warunków krytycznych samozapalania węgla w zrobach ścian, czyli takich po spełnieniu których może dojść do samozapalenia. Przyjęto, że znajdujący się w zrobach rozkruszony węgiel ma kształt płaskiej warstwy, sąsiadującej od stropu i spągu ze skałami.

Rozważania ograniczono do węgli charakteryzujących się niską zawartością wilgoci. Przyjęto prosty model kinetyki utleniania na powierzchni węgla wyrażony równaniem Arrheniusa. Model ten zakłada niezależność szybkości utleniania od ilości tlenu pochłoniętego przez węgiel. Szybkość reakcji zależy jedynie od temperatury , przy czym występujące w równaniu parametry zmieniają się po osiągnięciu przez węgiel temperatury krytycznej. W artykule przedstawiono matematyczny model samozagrzewania warstwy węgla w zrobach opisujący bilans ciepła w węglu oraz bilans tlenu i bilans ciepła w przepływających gazach. Tworzące model układy równań różniczkowych cząstkowych rozwiązywane są metodami numerycznymi. Opracowany program komputerowy umożliwia wykonywanie stosownych obliczeń. W pracy, na przykładzie węgla z pokładu 405 , przedstawiono sposób wyznaczania warunków krytycznych warstwy rozkruszonego węgla: grubości warstwy, zawartości tlenu w przepływających przez warstwę gazach oraz przewodności cieplnej otaczających skał.

Słowa kluczowe: samozapalanie, węgiel, model matematyczny, rozwiązania numeryczne, warunki krytyczne samozapalania

Nomenclature:

A	–	external surface of coal, m^2
C	–	volume fraction of oxygen in gases,
Co	–	volume fraction of oxygen in gases incoming to the coal layer,
c	–	specific heat, J/kg×K
D_c	–	diffusion coefficient of oxygen, m^2/s
D_r	–	thermal diffusivity coefficient , m^2/s
H	–	thickness of the layer of coal or rocks, m
L	–	length of the layer of coal, m
n	–	order of reaction,
R	–	reaction rate constant, 1/s
$T(x,y,t)$	–	temperature of coal, K
T_a	–	temperature of activation, K
T_{cr}	–	critical temperature, K
$U(x,y,t)$	–	temperature of gases, K
x,z	–	geometric coordinates, m
α	–	coefficient of heat transfer, W/(m^2×K)
β	–	coefficient of oxygen absorption on the coal surface,
λ	–	coefficient of thermal conductivity, W/m×K
v_f	–	gas flow rate, m/s
ρ	–	density, kg/m^3

Subscripts:

1	–	rocks in the floor,
2	–	rocks in the roof,

b	–	upper boundary,
t	–	lower boundary,
l	–	left side
r	–	right side
cr	–	critical temperature value
do	–	a range of temperatures below or equal to critical value,
in	–	initial value,
p	–	air,
po	–	a range of temperatures above critical value,
w	–	coal,
s	–	rocks.

Introduction

Spontaneous combustion of coal remains a serious problem for underground coal mines as it causes huge material losses and can put working mining crews in danger. There are known cases of methane ignition resulting from spontaneous combustion of coal, which in turn caused human losses. Spontaneous combustion of coal is a result of exothermic oxidation reaction. The process of self-ignition occurs when the flux of heat produced by the reaction exceeds the heat flux absorbed by the environment. This excess of heat raises the temperature of coal. That in turn accelerates the oxidation reaction, leading to a rapid temperature increase and finally to self-ignition of coal.

The more limited exchange of heat with environment (i.e. conditions closer to the adiabatic ones) the higher probability of spontaneous combustion. Apart from the conditions of heat exchange with the environment, a huge impact on the possibility of self ignition occurrence has a content of oxygen in gases flowing through the crushed coal as well as the natural susceptibility of coal to oxidation. A description of the phenomena leading to spontaneous combustion of coal is related to the theory of thermal explosion. Its creator, N.N. Semenov, introduced a concept of critical conditions. This theory was further developed by D.A. Frank-Kamieniecki, who in turn put forward a concept of a critical parameter. This theory constituted the starting point for numerous research studies, among others W. Kordylewski, Z. Krajewski (1980); W. Kordylewski, Z. Krajewski (1981); W. Kordylewski (1985). In the recent years, however, Frank-Kamieniecki theory has been subjected to criticism. Along with the development of electronic computing technology, numerical modeling became possible, and thus it became possible to determine the conditions of spontaneous combustion of coal. There is quite an extensive literature concerning a mathematical description of spontaneous heating and self ignition of coal. Previous works: Branny M. et al. (1995, 1997); Krishnaswamy S.K. et al. (1996); Rosema A. et al. (2001); Schmal D. et al. (1985); Schmidt M. et al. (2003); Smith M.A., Glasser D. (2005) were of a cognitive nature and intended to explain the mechanism of spontaneous combustion. In the recent years there have been reported a few works aimed at solving the specific practical issues. In the work of Yuan L., Smith A.C. (2008), the authors attempt to describe spontaneous combustion of coal in longwall gob areas. The work of Taraba B. et al. (2014) presents a description of the process of spontaneous heating of a coal stockpile.

1. Geometric model of a coal deposit

A flat layer of crushed coal with a thickness of H_w adjacent from one side to the rock layer with a thickness of H_1 and from the other side to the rock layer with a thickness of H_2, through which oxygen-containing gases flow at the rate v_f is taken into consideration. It is assumed that the flow through the layer is pumped, fixed in time and with a constant velocity profile in the cross-section of the layer. This flow is caused by the difference of aerodynamic potentials.
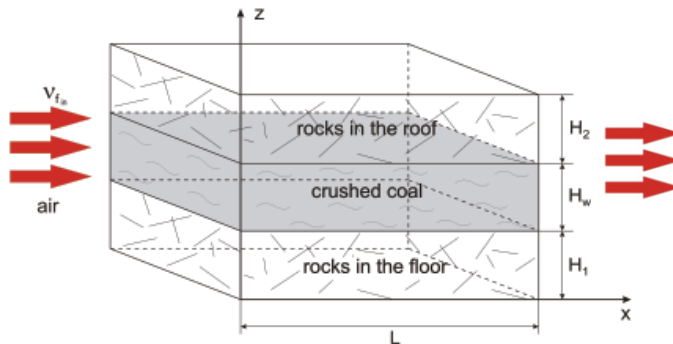
Fig. 1 A fragment of a gob area with crushed coal

A mathematical model which specifies temperature field $T(x,y,t)$ within the coal deposit, temperature $U(x,y,t)$ and concentration $C(x,y,t)$ of oxygen in flowing gases is taken into consideration. It takes account of coal oxidation, mass transport and diffusion processes as well as adsorption and heat exchange on the surface of the coal deposit.

The following notations are introduced:

$$z_1 = H_1, \; z_2 = H_1 + H_w, \; Z = H_1 + H_w + H_2 \qquad \text{(see Fig. 1)}$$

2. Kinetic model of oxidation and model of heat sources

A detailed description of oxidation and chemisorption processes is not a subject of this article. The heat produced by oxidation and chemisorption is expressed as:

$$E_r = mq_r(T)R_C \tag{1}$$

where:

q_r — heat of oxidation reaction,
m — porosity coefficient of crushed coal,
R_C — stream of absorbed oxygen.

The rate of oxygen absorption depends on the temperature T and the oxygen concentration C. Based on the experimental research studies a kinetics model of coal oxidation has been built:

$$R_C(T,C) = \begin{cases} R_{do} C^{n_{do}} e^{-T_{do}/T}, & T \le T_{cr}, \\ R_{po} C^{n_{po}} e^{-T_{po}/T}, & T > T_{cr}, \end{cases} \tag{2}$$

A method for determining the critical temperature is described in the works (Cygankiewicz, 2000).

Heat exchange between coal and a stream of flowing gases is described by the following relation:

$$E_\alpha = \alpha\, A\, (U - T) \tag{3}$$

The heat E_r evolves directly within the coal, whereas the heat E_α is absorbed by the flowing gases. In total, the heat released in the air is expressed as:

$$R_U = -E_\alpha \tag{4}$$

The heat evolved within the coal can be written as:

$$R_T = E_r + E_\alpha \tag{5}$$

3. Energy balance in the layer of coal

Energy balance in the self-heating layer of coal can be described by the following equations:

$$\begin{aligned} c_1\rho_1 \frac{\partial T}{\partial t} - \lambda_1 \frac{\partial^2 T}{\partial x^2} - \lambda_1 \frac{\partial^2 T}{\partial z^2} &= 0, && \text{for } 0 < x < L, \ 0 < z < z_1, \\ (1-m)\rho_{ws} \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left[\lambda \frac{\partial T}{\partial x}\right] - \frac{\partial}{\partial z}\left[\lambda \frac{\partial T}{\partial z}\right] &= R_T, && \text{for } 0 < x < L, \ z_1 < z < z_2, \\ c_2\rho_2 \frac{\partial}{\partial t}T - \lambda_2 \frac{\partial^2 T}{\partial x^2} - \lambda_2 \frac{\partial^2 T}{\partial z^2} &= 0, && \text{for } 0 < x < L, \ z_2 < z < Z. \end{aligned} \tag{6}$$

Equation (6) should be considered together with initial, boundary and compatibility conditions.

Initial conditions: $t = 0$:

$$\begin{aligned} T(x,z,0) &= T_{1in}, && \text{for } 0 \le x \le L, \ 0 \le z \le z_1, \\ T(x,z,0) &= T_{win}, && \text{for } 0 \le x \le L, \ z_1 \le z \le z_2, \\ T(x,z,0) &= T_{2in}; && \text{for } 0 \le x \le L, \ z_2 \le z \le Z, \end{aligned} \tag{7}$$

Boundary conditions on the left $x = 0$ and right $x = L$ side of the considered domain:

$$\begin{aligned} \frac{\partial}{\partial x}T(0,z,t) &= \frac{\partial}{\partial x}T(L,z,t) = 0, && \text{for } 0 < z < z_1, \\ \lambda \frac{\partial}{\partial x}T(0,z,t) - \alpha_l(t)(T(0,z,t) - T_l(t)) &= 0, && \\ \lambda \frac{\partial}{\partial x}T(L,z,t) + \alpha_r(t)(T(L,z,t) - T_r(t)) &= 0, && \text{for } z_1 < z < z_2, \\ \frac{\partial}{\partial x}T(0,z,t) &= \frac{\partial}{\partial x}T(L,z,t) = 0, && \text{for } z_2 < z < Z; \end{aligned} \tag{8}$$

766

Boundary conditions at the lower $z = 0$ and upper $z = Z$ boundary of the considered domain:

$$
\begin{aligned}
\lambda_1 \frac{\partial}{\partial z} T(x,0,t) - \alpha_b(t)(T(x,0,t) - T_b(t)) = 0, \\
\lambda_2 \frac{\partial}{\partial z} T(x,Z,t) + \alpha_t(t)(T(x,Z,t) - T_t(t)) = 0,
\end{aligned}
\qquad \text{for } 0 \le x \le L
\tag{9}
$$

Compatibility conditions at the coal-rock phase boundary $z = z_1$ and $z = z_2$:

$$
\begin{aligned}
T(x,z_1-0,t) = T(x,z_1+0,t), \quad \lambda_1 \frac{\partial}{\partial z} T(x,z_1-0,t) = \lambda \frac{\partial}{\partial z} T(x,z_1+0,t), \\
T(x,z_2-0,t) = T(x,z_2+0,t), \quad \lambda \frac{\partial}{\partial z} T(x,z_2-0,t) = \lambda_2 \frac{\partial}{\partial z} T(x,z_2+0,t),
\end{aligned}
\qquad \text{for } 0 \le x \le L
\tag{10}
$$

The following functions are introduced:

$$
D_T(x,z,t) = \begin{cases}
\dfrac{\lambda_1}{\rho_1 c_1}, & 0 < z < z_1, \\[2mm]
\dfrac{\lambda(x,z,t)}{\rho_w c_{ws}}, & z_1 < z < z_2, \\[2mm]
\dfrac{\lambda_2}{\rho_2 c_2}, & z_2 < z < Z,
\end{cases}
\tag{11}
$$

$$
H(x,z,t) = \begin{cases}
0, & 0 < z < z_1, \\[2mm]
\dfrac{0.5 R_T}{\rho_w(c_{ws} + c_w X)}, & z_1 < z < z_2, \\[2mm]
0, & z_2 < z < Z,
\end{cases}
\tag{12}
$$

Taking into account the relations (11 and 12), equation (6) can be written as:

$$
\frac{\partial T}{\partial t} - \frac{1}{B} \frac{\partial}{\partial x}\left[D_T \frac{\partial T}{\partial x} \right] - \frac{1}{B} \frac{\partial}{\partial z}\left[D_T \frac{\partial T}{\partial z} \right] = 2H,
$$
$$
\text{for } 0 < x < L, \ 0 < z < Z, \ z \neq z_1, \ z \neq z_2
\tag{13}
$$

The following notations are introduced:

$$
\begin{array}{lll}
d_{l1} = 0, & e_{l1} = 1, & f_{l1} = 0, \\
d_{r1} = 0, & e_{r1} = 1, & f_{r1} = 0, \\
d_l(t) = -\alpha_l(t), & e_l(z,t) = \lambda(0,z,t), & f_l(t) = -\alpha_l(t)\, T_l(t), \\
d_r(t) = \alpha_r(t), & e_r(z,t) = \lambda(L,z,t), & f_r(t) = \alpha_r(t)\, T_r(t), \\
d_{l2} = 0, & e_{l2} = 1, & f_{l2} = 0, \\
d_{r2} = 0, & e_{r2} = 1, & f_{r2} = 0
\end{array}
\tag{14}
$$

$$d_b(t) = -\alpha_b(t), \quad e_b = \lambda_1, \quad f_b(t) = -\alpha_b(t)T_b(t),$$
$$d_t(t) = \alpha_t(t), \quad e_t = \lambda_2, \quad f_t(t) = \alpha_t(t)T_t(t)$$

(15)

Using (14), boundary conditions (8) can be written as follows:

$$d_{l1}T(0,z,t) + e_{l1}\frac{\partial}{\partial x}T(0,z,t) = f_{l1},$$

$$\text{for } 0 \le z < z_1,$$

$$d_{r1}T(L,z,t) + e_{r1}\frac{\partial}{\partial x}T(L,z,t) = f_{r1},$$

$$d_l(t)T(0,z,t) + e_l(z,t)\frac{\partial}{\partial x}T(0,z,t) = f_l(t),$$

$$\text{for } z_1 \le z \le z_2,$$

(16)

$$d_r(t)T(L,z,t) + e_r(z,t)\frac{\partial}{\partial x}T(L,z,t) = f_r(t),$$

$$d_{l2}T(0,z,t) + e_{l2}\frac{\partial}{\partial x}T(0,z,t) = f_{l2},$$

$$\text{for } z_2 < z \le Z$$

$$d_{r2}T(L,z,t) + e_{r2}\frac{\partial}{\partial x}T(L,z,t) = f_{r2},$$

Using (15), boundary conditions (9) can be written as:

$$d_b(t)T(x,0,t) + e_b\frac{\partial}{\partial z}T(x,0,t) = f_b(t),$$

$$\text{for } 0 \le x \le L$$

(17)

$$d_t(t)T(x,Z,t) + e_t(x,t)\frac{\partial}{\partial z}T(x,Z,t) = f_t(t),$$

4. Oxygen balance in a stream of flowing gases

Concentration of oxygen in a stream of gases is described by the following balance equation:

$$\frac{\partial C}{\partial t} - D_C\frac{\partial^2 C}{\partial x^2} - D_C\frac{\partial^2 C}{\partial z^2} + v_f\frac{\partial C}{\partial x} = -R_C, \quad \text{for } 0 < x < L, \ z_1 < z < z_2$$

(18)

Equation (18) should be considered together with initial and boundary conditions.
Initial conditions $t = 0$:

$$C(x,z,0) = C_{in}, \quad \text{for } 0 \le x \le L, \ z_1 \le z \le z_2$$

(19)

Boundary conditions:

$$C(0,z,t) = C_0(t), \quad \frac{\partial}{\partial x}C(L,z,t) = 0, \quad \text{for } z_1 \le z \le z_2;$$

$$D_C\frac{\partial}{\partial z}C(x,z_1,t) - \beta_1 C(x,z_1,t) = 0,$$

$$\text{for } 0 \le x \le L$$

(20)

$$D_C\frac{\partial}{\partial z}C(x,z_2,t) + \beta_2 C(x,z_2,t) = 0,$$

768

A function is introduced:

$$G(x,z,t) = -0.5R_C,$$ (21)

Taking into account (21), equation (18) can be written as follows:

$$\frac{\partial C}{\partial t} - D_C \frac{\partial^2 C}{\partial x^2} - D_C \frac{\partial^2 C}{\partial z^2} + v_f \frac{\partial C}{\partial x} = 2G, \quad \text{for } 0 < x < L, \ z_1 < z < z_2$$ (22)

The following notations are introduced:

$$
\begin{aligned}
p_l &= 1, & s_l &= 0, & g_l(t) &= C_0(t), \\
p_r &= 0, & s_r &= 1, & g_r &= 0, \\
p_b &= -\beta_1, & s_b &= D_C, & g_b &= 0, \\
p_t &= \beta_2, & s_t &= D_C, & g_t &= 0
\end{aligned}
$$ (23)

Using (23), boundary conditions (20) can be written as:

$$
\begin{aligned}
&p_l C(0,z,t) + s_l \frac{\partial}{\partial x} C(0,z,t) = g_l(t), \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{for } z_1 \le z \le z_2; \\
&p_r C(L,z,t) + s_r \frac{\partial}{\partial x} C(L,z,t) = g_r, \\
&p_b C(x,z_1,t) + s_b \frac{\partial}{\partial z} C(x,z_1,t) = g_b(t), \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{for } 0 \le x \le L \\
&p_t C(x,z_2,t) + s_t \frac{\partial}{\partial z} C(x,z_2,t) = g_t(t),
\end{aligned}
$$ (24)

5. Energy balance in the air stream

Energy balance in the air stream is described by the balance equation:

$$\rho_p c_{ps} \left(\frac{\partial U}{\partial t} + v_f \frac{\partial U}{\partial x} \right) = R_U, \quad \text{for } 0 < x < L, \ z_1 < z < z_2$$ (25)

Equation (25) should be considered together with initial and boundary conditions.
Initial conditions $t = 0$:

$$U(x,z,0) = U_{in}, \quad \text{for } 0 \le x \le L, \ z_1 \le z \le z_2$$ (26)

Boundary conditions:

$$U(0,z,t) = U_0(t), \quad \text{for } z_1 \le z \le z_2$$ (27)

A function is introduced:

$$F = \frac{R_U}{\rho_p \, c_{ps}}$$ (28)

Taking into account (28), equation (25) can be written as follows:

$$\frac{\partial}{\partial t}U + v_f \frac{\partial}{\partial x}U = F, \quad \text{for } 0 < x < L, \; z_1 < z < z_2 \tag{29}$$

6. Discretization

The following increments are introduced: $\Delta_x, \Delta_z, \Delta_t$ along O_x, O_z, O_t axes, respectively, and the domain of continuous variables is replaced with the finite set of nodes. The number of nodes is determined along each axis as well as the position of the coal-rock phase boundary – J_1, J_2.

$$N = \left[T_f / \Delta_\tau \right], \; I = \left[L / \Delta_x \right], \; J_1 = \left[z_1 / \Delta_z \right], \; J_2 = \left[z_2 / \Delta_z \right], \; J = \left[Z / \Delta_z \right] \tag{30}$$

where:

T_f — final time,
[] — denotes the integer part of a number.

The coordinates of the nodes x_i, z_j, t_n are placed within the following introduced sets:

$$\begin{aligned} x_i &= \Delta_x i, \; 0 \le i \le I, \\ z_j &= \Delta_z j, \; 0 \le j \le J, \\ t_n &= \Delta_t n, \; 0 \le n \le N \end{aligned} \tag{31}$$

The values of the dependent and independent variables in the nodes x_i, z_j, t_n correspond with the indices i, j, n. For convenience, they can be either subscripts or superscripts.

7. Calculation example

The critical conditions are being defined for spontaneous combustion of the coal layer in a seam 405. Coal from this seam contains small amount of moisture. Below are presented geometric parameters of the layer used for calculations, determined by the laboratory studies of the coal and rocks properties.

- Time and geometric parameters

Time	T_f	= 100, 200, 300, 400, 1000 h
Length of the layer	L_w	= 6 m
Thickness of the layer of coal	H_w	= 0.5, 0.6, 0.7 m
Thickness of the layer of rocks	H_1	= 1.0 m
Thickness of the layer of rocks	H_2	= 1.0 m

- Physical parameters of coal and rocks

Porosity coefficient of crushed coal	m	= 0.45
Specific heat of air	C_{ps}	= 1005.6 J/kgK
Specific heat of coal	C_{ws}	= 1280.0 J/kgK
Density of coal	ρ_{ws}	= 815 kg/m^3
Coefficient of thermal conductivity of coal	λ	= 0.3 W/mK

Specific heat of rocks in the roof	c_1	= 2000 J/kgK
Specific heat of rocks in the floor	c_2	= 2000 J/kgK
Density of rocks in the roof	ρ_1	= 2000 kg/m³
Density of rocks in the floor	ρ_2	= 2000 kg/m³
Coefficient of thermal conductivity of rocks in the floor	λ_1	= 1.0,1.2,1.4,1.5,1.6,1.8,2.0 W/mK
Coefficient of thermal conductivity of rocks in the floor	λ_2	= 1.0,1.2,1.4,1.5,1.6,1.8,2.0 W/mK
Coefficient of oxygen diffusion in air	D_c	= 1.0^{-5} m²/s

- Initial parameters

Initial temperature of coal	T_{win}	= 300 K
Initial temperature of rocks in the roof	T_{1in}	= 300 K
Initial temperature of rocks in the floor	T_{2in}	= 300 K
Initial temperature of air	U_{in}	= 300 K
Initial concentration of O_2	C_{in}	= 0.0
Gas flowrate	v_{fin}	= 0.0006 m/s

- Parameters of oxidation kinetics

Heat of reaction	q_r	= 7.6 10^6 J/m³
Reaction rate constant	R_{do}	= 0.12 1/s
Reaction rate constant	R_{po}	= 1875 1/s
Activation temperature	T_{do}	= 1490 K
Activation temperature	T_{po}	= 4980 K
Order of reaction	n_{do}	= 1.6
Order of reaction	n_{po}	= 1.6
Critical temperature	T_{cr}	= 360 K
Heat transfer coefficient	$\alpha_{l,r,t}$	= 0 W/m²K

Calculation results

The results of performed calculations are presented in Fig. 2-7. Fig. 2 shows temperature distribution in the heated coal and surrounding rocks. Calculations were carried out for the coal layer with the following thicknesses: H_w = 0,5; 0,6 and 0,7 m. The calculation times were 100, 200, 300 and 400 hours. To simplify calculations, the thermal conductivity of rocks in the roof was assumed to be equal to that in the floor and amounted to 1,0 W/mK. As shown in Fig. 2, spontaneous combustion proceeded at its maximum and minimum rate, respectively, in the thickest (0,7 m) and in the thinnest layer (0,5 m).

Fig. 3 demonstrates distributions of oxygen content in gases flowing through the examined deposit of crushed coal. They correspond to the temperature distributions shown in Fig. 2.

Fig. 4 presents the results of studies on the impact of a thickness of the coal layer from a seam 405 H_w deposited in the gob area on the predicted course of spontaneous combustion development. The latter is shown as a dependence of the maximum temperature of coal within the deposit on time. The values of a coal layer thickness H_w used in calculations were as follows: 0,3; 0,4; 0,5; 0,6 and 0,7 m, the oxygen volume fraction in the stream of incoming air was 0,2 and the coefficient of thermal conductivity of rocks in the roof and floor was λ = 1,0 W/mK. As it can be seen from Fig 4., the thicker layer of coal (i.e. the closer the conditions to the adiabatic
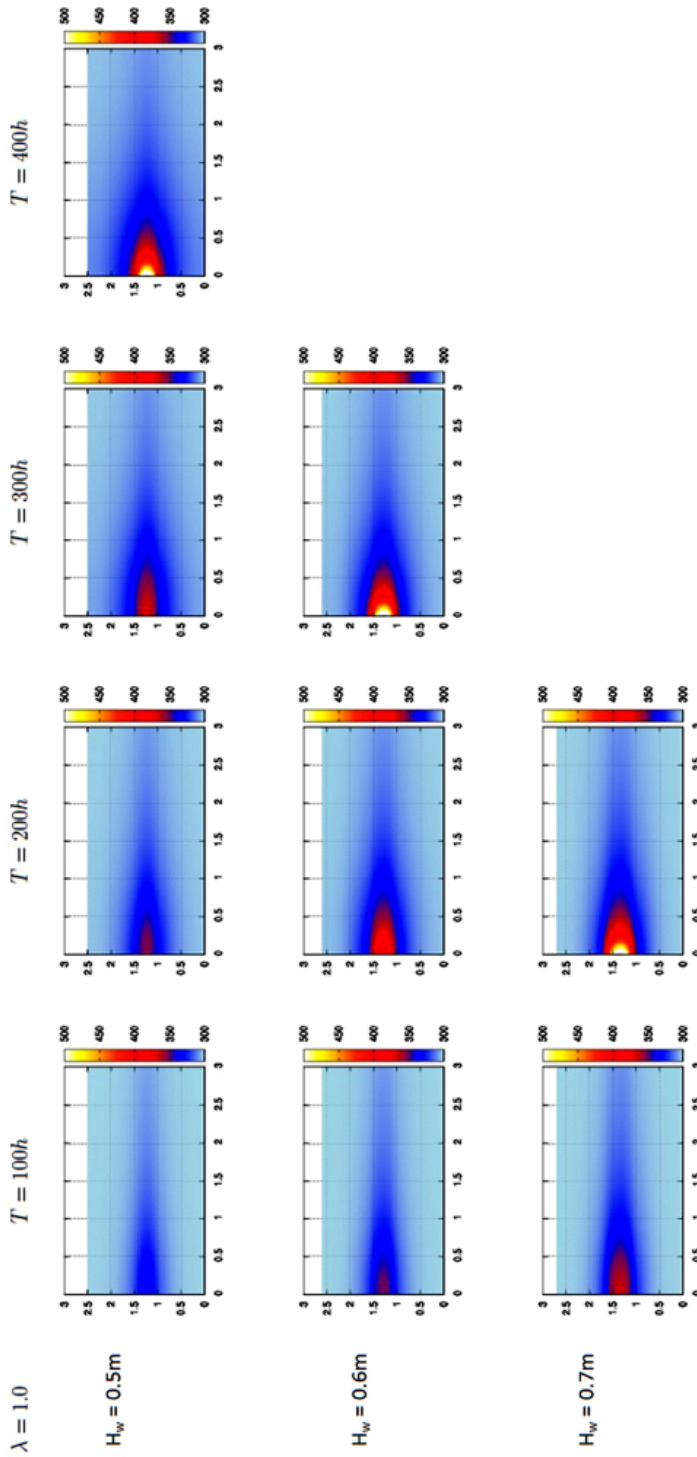
Fig. 2 Temperature distribution in the crushed coal deposit with thicknesses of H_w = 0,5; 0,6 and 0,7 m and in surrounding rocks during spontaneous heating, after 100, 200, 300 and 400 hours from its beginning
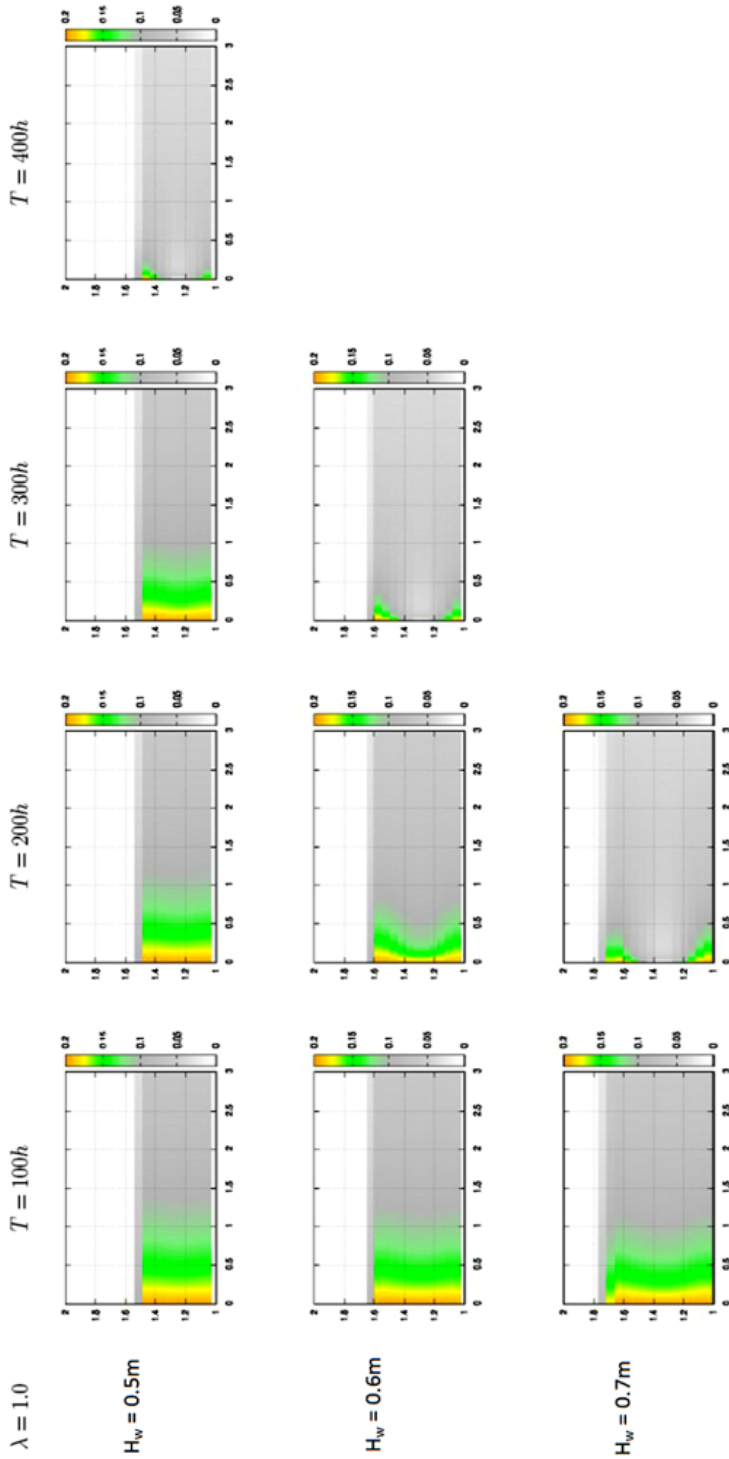
Fig. 3 Oxygen concentration distribution in gases flowing through the crushed coal deposit with thicknesses of H_w = 0,5; 0,6 and 0,7 m during spontaneous heating, after 100, 200, 300 and 400 hours from its beginning

ones), the more rapid process of spontaneous heating. There exists a certain critical thickness of the coal layer, below which spontaneous combustion will not occur.

Fig. 5 shows the impact of oxygen content in the air incoming to the coal layer on the development of spontaneous combustion process. The higher is the concentration of oxygen the faster development of this process. As with a thickness of the coal layer, there is a critical value of oxygen concentration, below which spontaneous combustion will not occur.

Fig. 6 shows the influence of thermal conductivity of rocks on the course of spontaneous heating of the coal layer with a thickness $H_w = 0,6$ m from a seam 405. The assumed volume fraction of oxygen in the air incoming to the coal deposit was 0,2. As can be noticed from Fig. 6, an increase in thermal conductivity of rocks slows down the process of self-heating. For simplicity of calculation, the thermal conductivity of rocks in the roof λ_1 was assumed to be equal to the thermal conductivity of rocks in the floor λ_2. It is, of course, possible to perform calculations for the case when $\lambda_1 \neq \lambda_2$.

Fig. 7 contains summarized values of critical conditions of spontaneous combustion of coal from a seam 405 in longwall gob areas. The values of a coal layer thickness H_w were plotted on the X axis against the values of thermal conductivity coefficient of surrounding rocks λ on the Y axis. For particular values of oxygen concentration in the stream of incoming air the curves of critical parameters were determined. For example, a coal layer thickness $H_w = 1,0$ m, oxygen concentration $C = 0,1$ and thermal conductivity of rocks $\lambda = 1,14$ W/mK constitute the critical conditions of spontaneous combustion of coal in the seam.
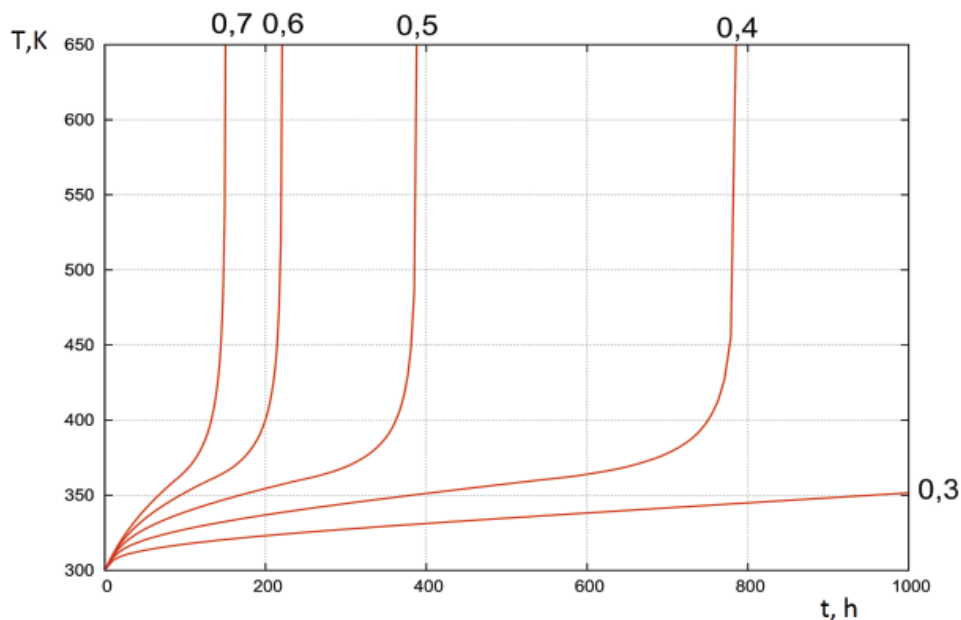

Fig. 4 Impact of a thickness H_w of the coal layer remaining in the gob on the predicted course of spontaneous heating of the coal layer ($H_w = 0,3, 0,4, 0,5, 0,6, 0,7$ m)
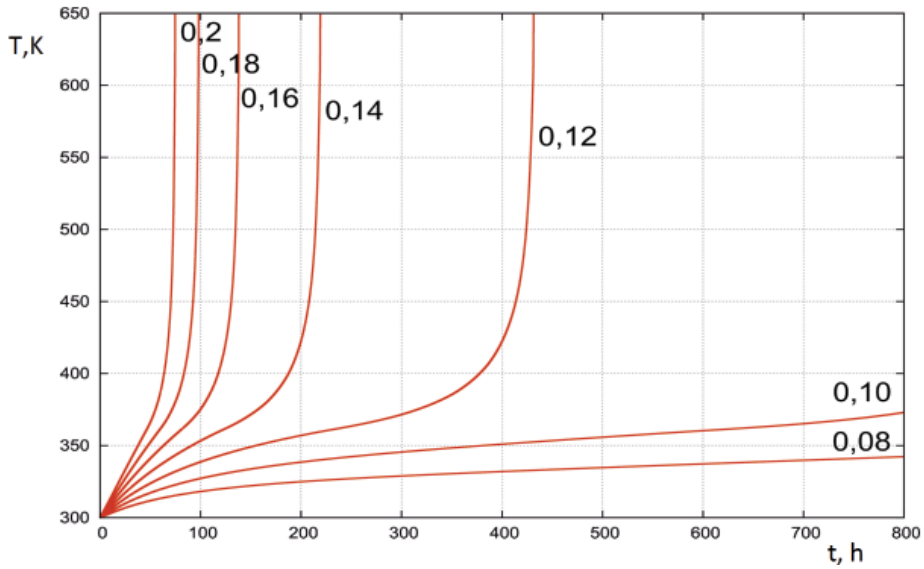$\lambda_1 = \lambda_2 = 1,0$ W/mK

774

Fig. 5 Impact of oxygen volume fraction in a stream of incoming air on the predicted course of
spontaneous heating of the coal layer
(H_w = 1,0 m , $\lambda_1 = \lambda_2$ = 1,5 W/mK , Co = 0,08; 0,10; 0,12; 0,14; 0,16; 0,18; 0,20)

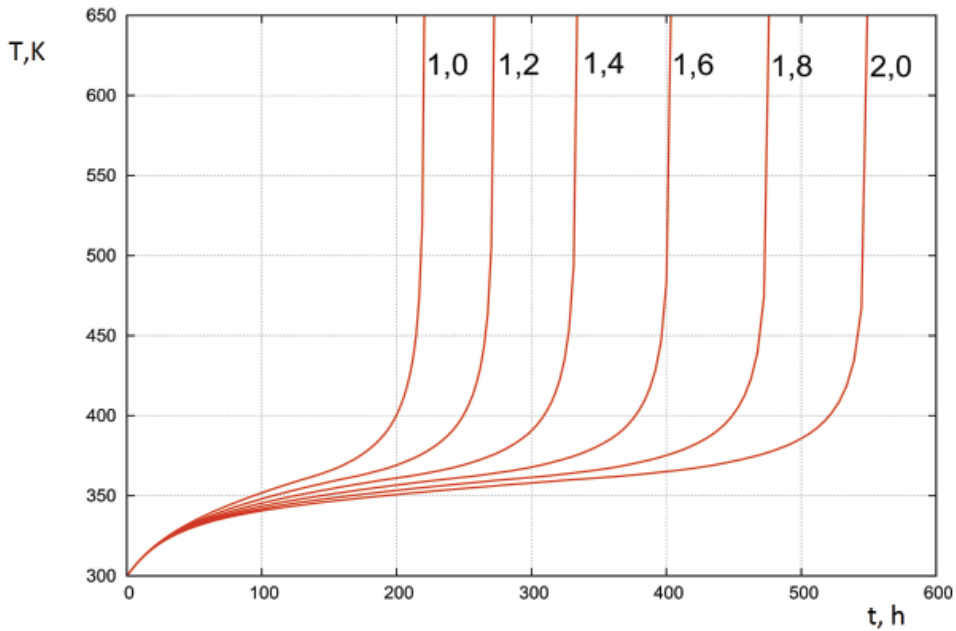

Fig. 6 Impact of the thermal conductivity coefficient l on the predicted course of spontaneous
heating of the coal layer
(H_w = 0,6m, $\lambda_1 = \lambda_2$ = 1,0; 1,2; 1,4; 1,6; 1,8; 2,0 W/mK)
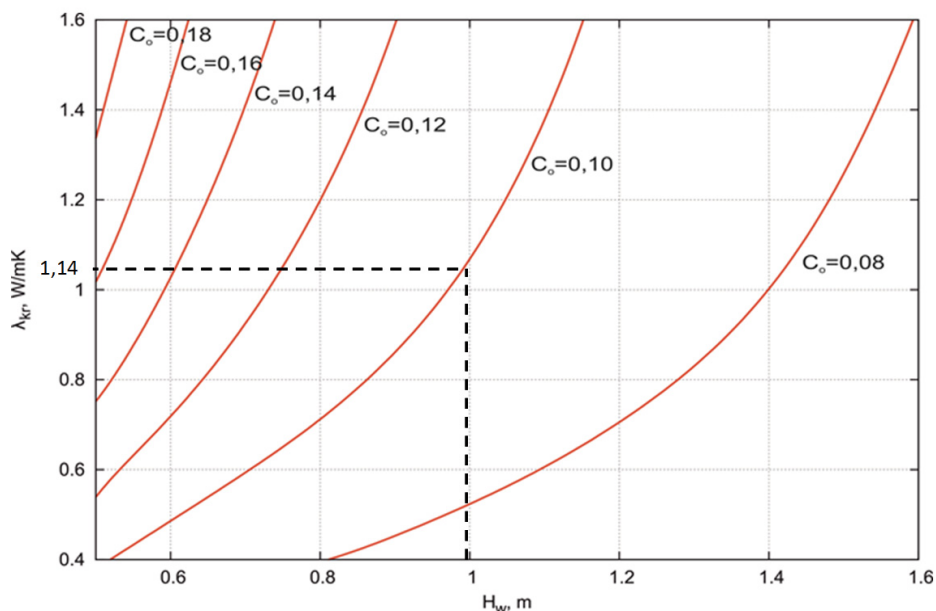
Fig. 7 The critical conditions of spontaneous combustion of coal in the gob area in seam 405

8. Summary

The method presented in this paper for determining the critical conditions of spontaneous combustion of the flat layer of crushed coal can be useful in the mining practice to evaluate the risk of endogenous fire occurrence in longwall gob areas. This risk may be posed by the coal entering a gob from located closely over the roof the non-balance seam of remained thin coal bed, or by the coal which got to a gob in consequence of geological disturbances. However, one should not forget about the simplifying assumptions adopted in this work. They limit the application range of the presented method to coal seams with a low content of moisture, for which the process of evaporation can be ignored in the calculations. Other assumptions made in this work include that the rate of coal oxidation is fixed in time and that the aspect of oxygen transport in coal particles with a diameter greater than 2 mm is disregarded.

The advantage of the presented method lies in its simplicity and relatively few and easily determined parameters of coal and surrounding rocks present in the mathematical model. One can therefore expect that this method will find application in engineering calculations. However, its verification on the basis of mining examinations is required. It is also worthwhile to undertake further studies on the development of more complex mathematical models of spontaneous combustion which would take into account the variability of coal oxidation rate, evaporation of moisture and its influence on spontaneous combustion, as well as oxygen diffusion within coal particles.

776

Acknowledgments

References

Branny M., Cygankiewicz J., Wacławik J., 1995. *One dimensional model of endogenic fire in gob areas or coal cracks*. Arch. Min. Sci., Vol. 40, No 1, p. 39-51.

Branny M., Cygankiewicz J., Piotrowski A., Wacławik J., 1997. *Numerical simulation of low-temperature oxidation of coal (simplified two-dimensional issue)*. Arch. Min. Sci. 42, No 4, p. 501-514.

Cygankiewicz J., 2000. *Studies on low-temperature spontaneous heating of hard coals in Central Mining Institute*. School of Underground Mining Library, p. 5-31.

Cygankiewicz J., 2000. *About determination of susceptibility of coals to spontaneous combustion using an adiabatic test method*. Arch. Min. Sci. Vol. 45, No , p. .

Cygankiewicz J., 2005. *Determination of heat stream produced by oxidation of coal in mining workings*. Materials from the 10th session of International Bureau of Mining Thermophysics, p. 29-42.

Cygankiewicz J., Knechtel J., 2014. *The effect of temperature of rocks on microclimatic conditions in long gate roads and galleries in coal mines*. Arch. Min. Sci., Vol. 59, No 1, p. 189-216

Kordylewski W., Krajewski Z., 1980. *Determination of critical conditions of thermal explosion*. Fuel and Energy Management, No 2, p. 15-19.

Kordylewski W., Krajewski Z., 1981. *Thermal ignition of self-heating porous slab*. Combustion and Flame, 41, p. 113-122.

Kordylewski W., 1985. *Theory of thermal explosion and its applications*. Publishing of Wroclaw University of Technology, Institute of Heat Engineering and Fluid Mechanics, t. 26, Monography 9.

Krishnaswamy S.K., Bhat S., Gunn R.D., Agarwal P.K., 1996. *Low-temperature oxidation of coal. 3. Modeling spontaneous combustion in coal stockpiles*. Fuel, 75, p. 353-362.

Rosema A., Guan H., Veld H., 2001. *Simulation of spontaneous combustion, to study the causes of coal fires in the Rujigou Basin*. Fuel, 80(1), p. 7-16.

Schmal D., Duyzer J.H., van Heuven J., 1985. *A model for the spontaneous heating of coal*. Fuel, 64, p. 963-972.

Schmidt M., Lohrer C., Krause U., 2003. *Self-ignition of dust at reduced volume fractions of ambient oxygen*. Journal of loss prevention in the process industries, 16, p. 141-147.

Smith M.A., Glasser D., 2005. *Spontaneous combustion of carbonaceous stockpiles. Part II. Factors affecting the rate of the low-temperature oxidation reaction*. Fuel, 84, p. 1161-1170.

Taraba B., Michale Z., Michalcová V., Blejchař T., Bojko M., Kozubková M., 2014. *CFD simulations of the effect of wind on the spontaneous heating of coal stockpiles*. Fuel, vol. 118, no. 2, p. 107-112.

Yuan L., Smith A.C., 2008. *Numerical study on effects of coal properties on spontaneous heating in longwall gob areas*. Fuel, 87, 15-16, p. 3409-3419.