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THE FIRST STAGE OF EXOGENOUS UNDERGROUND FIRE – THEORETICAL APPROACH TO LAYER MODEL

Summary. A discussion about the layer model which – even though it is most often used for fire in compartments – can be adapted to exogenous conditions of the fire in the mining excavation is presented in the article. This model is a simplified case consideration of the initial phase of development of the fire. Using the equations of conservation of mass and energy, and knowing the basic parameters of the fire, e.g. the fire load – temperature of the upper and the lower layer during the fire can be calculated. Applied equations and assumptions indicate that at the first stage of the fire (when it is tread as point) there is a lack of smoke emission or it is negligible therefore application of smoke detectors is insufficient for fire prevention purposes.

The example of belt conveyor fire has been selected as the result of work conducted by Institute of Mining of Silesian University of Technology in frames of Research for Coal and Steel Programme - EDAFFIC – "Early Detection And Fighting of Fires in Belt Conveyors", RFCR-CT-2008-00002 in years 2008-2011.

PIERWSZA FAZA PODZIEMNEGO POŻARU EGZOGENICZNEGO – TEORETYCZNE PODEJŚCIE DO MODELU WARSTWOWEGO

Streszczenie. W artykule przedstawiono rozważania nad modelem warstwowym pożaru, który – mimo że jest stosowany najczęściej przy pożarach pomieszczeń – może być przystosowany do warunków pożaru egzogenicznego w wyrobisku górniczym. Model ten jest uproszczonym przypadkiem dyskusji nad początkową fazą rozwoju pożaru. Przy zastosowaniu równań zachowania masy i energii oraz znając podstawowe parametry pożaru, np. gęstość obciążenia ogniowego, można wyliczyć temperaturę warstw dolnej i górnej. Zastosowane równania i uproszczenia wskazują, że przy początkowej fazie pożaru, kiedy jest on traktowany punktowo, emisja dymu nie występuje bądź jest ona na tyle znikoma, że w celu przeciwdziałania takim pożarom, należy stosować czujki temperatury, a reakcja czujek dymu może być znacznie spóźniona. W artykule omówiono przykład pożaru przenośnika taśmowego, będącego rezultatem prac Instytutu Eksploatacji Złóż w ramach Funduszu Węgla i Stali, w programie badawczym EDAFFIC – "Early Detection And Fighting of Fires in Belt Conveyors", RFCR-CT-2008-00002, prowadzonym w latach 2008-2011.

1. Introduction

The theories about fire spread can be divided into two main groups.

a) Chemical – where equations of chemical kinetics are the basis,

b) Heat – where equations of energy conservation are the basis.

Heat theory is under elaboration in this article.

The heat models can be divided also into two main groups.

a) Probabilistic – based on calculus of probability,

b) Deterministic – physical model.

The zone (layer) model is a type of deterministic model and it will be discussed below.

According to belt conveyor cases of fire in underground coal mine [EDDAFIC Final Report 2011] – it has been selected as a source in an excavation. Layer model is crucial to understand behavior of fire at its first stage, where immediate reaction and application of handy fire suppressors may avoid large scale of damage.

At the first stage of belt conveyor fire spread, there is emission of: smoke, gases, small amount of thermal energy and radiation. Smoke and gases are being diluted by ventilation air stream and heat is being dissipated there. In spite of constant and slow increase of smoke, gases and temperature, there is creation of successive states of balance of the system "source of heat – flammable ambience". The system is being evaluated as lasting in states of stable balance. However, it is unstable [Dziurzyński, Krawczyk 2001].

This stage of fire has been named the first stage. It is characterized by deficiency of fuel because contact surface of source of heat is limited. But existing constantly excess of air causes intensive heat remove.

The model which is under discussion here is based on Wade and Barnet [Wade, Barnett 1997] conception – the fire is treat as medium which transports the products of combustion from combustion zone and sucked diffusion air from lower to upper layer.

2. Assumptions

The conception of a mathematical model of a fire in an underground excavation (especially in a gallery with longitudinal ventilation) is similar to the model of tunnel ventilation during a fire [Beard et all 1995, Kunsch 2002] and similar to the process of fire in any compartment [Janssens 2000, Fangrat 2001] with one horizontal size significantly larger than others and with one opening – for example a door. However, the model must fit certain mining conditions and there are several necessary assumptions (see fig. 2.1):

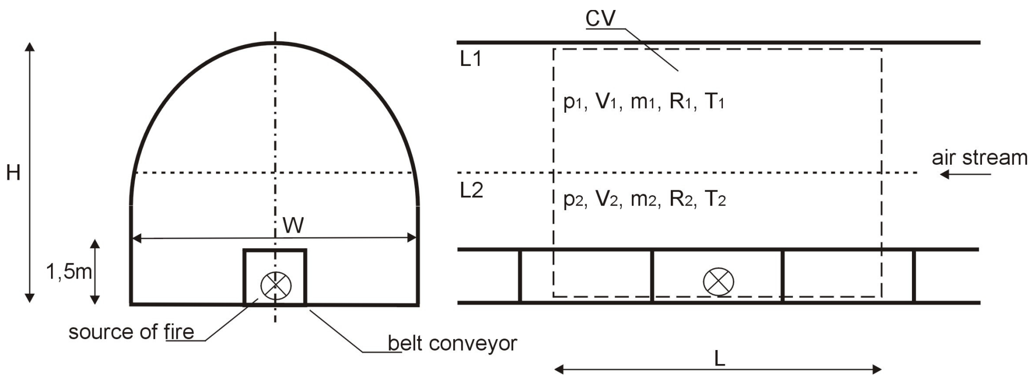

Fig. 2.1. View of the excavation (explanation of symbols below and at the next page)
Rys. 2.1. Schemat wyrobiska (wyjaśnienie oznaczeń poniżej i na następnej stronie)

a) Control volume (assigned as CV) comprises two layers (the interface between two layers is relatively sharp), and the belt conveyor is in the lower layer. The parameters of the upper layer (L1) are: p_1, V_1, m_1, T_1. The parameters of the lower layer (L2) are: p_2, V_2, m_2, T_2. The parameters are considered uniform in each layer.

   The cross-sectional area must be comparable to typical shape of an excavation and it is necessary to know equipment mounted in the excavation. It is assumed that the excavation is empty except for a belt conveyor (see fig. 2.1). The belt conveyor is simplified to a rectangle box. It is parallel to the floor and to the top of an excavation.
b) Early stage of fire is under consideration, therefore the mixing of layers is ignored. The moisture content is also ignored.
c) According to typical behavior of a fire at early stage, the air is entrained below the interference into the flame and plume at a rate that exceeds the rate needed for complete combustion of the fuel volatiles.
d) Air stream is forced by ventilation and it is stable state. The direction of air velocity is parallel to the excavation. In order to obtain mass flow, volume flow and velocity, it is needed to know the air density and the cross-section area.
e) The direction of the smoke produced during a fire is the same as the direction of the air flow.
f) Fire gases near the burning belt conveyor have the same temperature and density.

g) The fire must have set fuel mass loss rate M_{FL} but for simplification it is assumed at early stage of the fire as zero. Radiation and convection from the fire to the gases near conveyor are considered, but at early stage they may be disregarded. However, the radiation from the fire and convection are calculated on the basis of principle engineering equations. To obtain the amount of energy released during the entire time of the fire, the conception of the fire load is under consideration.

h) Fire is treated as a point and it is at early stage, so the combustion products flow according to the direction of the ventilation stream.

Conservation of mass and conservation of energy are applied in the CV in order to obtain the equations involved during the early stage of a conveyor belt fire in an underground excavation, given a non linear model of fire spread in a gallery.

Because the total volume of the excavation is fixed, the following relations exist between the volumes of lower and upper layer:

$$V_1 + V_2 = V = L \cdot 0{,}8 \cdot H \cdot W \tag{2.1}$$

where:

V_1 – volume of upper layer [m^3],

V_2 – volume of lower layer [m^3],

V – volume of the excavation [m^3],

L – length of the excavation in CV [m],

H – the highest height of the excavation [m],

W – width of the excavation at height, for example: 1,5 m [m],

0,8 – cross sectional coefficient for ŁP type of support.

Changes in pressure and moisture during the fire can be disregarded because of assumed ventilation [Janssens 2000, Wacławik 2010].

Mixing between the layers is usually minimal and it can be ignored [Janssens 2000], therefore two equations of state for both layers can be presented:

$$p_1 V_1 = m_1 R_1 T_1 \tag{2.2}$$

where:

p_1 – pressure of upper layer [Pa]

m_1 – mass of upper layer [kg]

R_1 – gas constant of upper layer [J (kgK)$^{-1}$]

T_1 – temperature of upper layer [K],

and

$$p_2 V_2 = m_2 R_2 T_2 \tag{2.3}$$

where:

p_2 – pressure of lower layer [Pa]

m_2 – mass of lower layer [kg]

R_2 – gas constant of lower layer [J (kgK)$^{-1}$]

T_2 – temperature of lower layer [K].

It must be noticed that value of R_2 is changing in time, so additional equations of conservation of mass must be solved during detailed calculations.

3. Conservation of mass

Mass in a layer must equal the sum of added and removed mass from a layer.
It can be express by equation (3.1).

$$m_L = m_A + m_R \tag{3.1}$$

where:

m_L – mass in a layer, [kg]

m_A – mass added to a layer, [kg]

m_R – mass removed from a layer, [kg].

Detailed diagram of mass conservation during the early stage of a conveyor belt fire in an underground excavation is presented in fig.3.1.

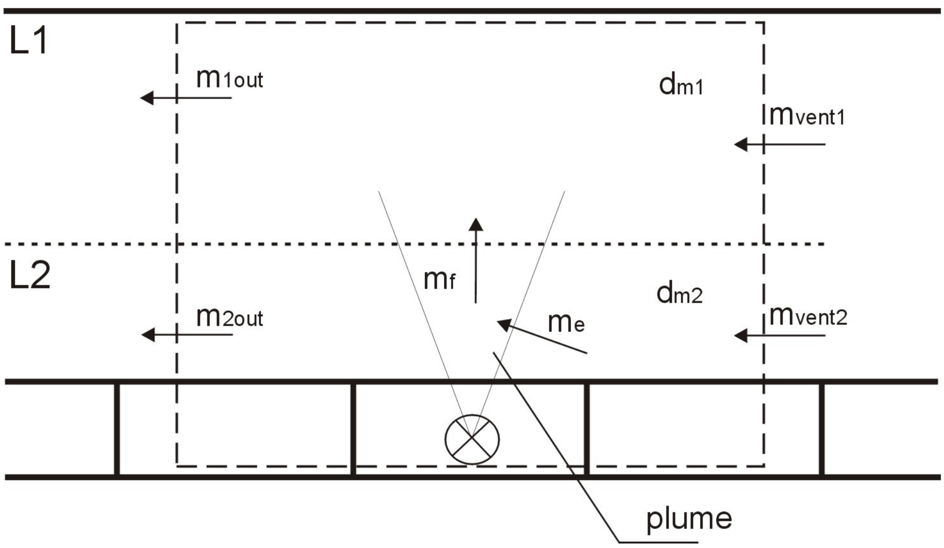

Fig. 3.1. Graphical representation of mass conservation during early stage of a conveyor belt fire in an underground excavation

Rys. 3.1. Graficzne przedstawienie zachowania masy podczas początkowej fazy pożaru przenośnika taśmowego w wyrobisku górniczym

Relations given in fig.3.1 are represented by the system of equations (3.2).

$$\begin{aligned} \frac{dm_1}{dt} &= \dot{m}_e + \dot{m}_f - \dot{m}_{1out} + \dot{m}_{vent1} \\ \frac{dm_2}{dt} &= \dot{m}_{vent2} - \dot{m}_e - \dot{m}_{2out} \end{aligned} \tag{3.2}$$

where:

$\frac{dm_1}{dt}$ – change of mass in the upper layer, [kg]

$\frac{dm_2}{dt}$ – change of mass in the lower layer, [kg]

$\dot{m}_e$ – mass flow of the air entrained to the plume, [kg/s]

$\dot{m}_f$ – plume of mass flow, [kg/s]

$\dot{m}_{1out}$ – mass flow leaving CV in the upper layer, [kg/s]

$\dot{m}_{2out}$ – mass flow leaving CV in the lower layer, [kg/s]

$\dot{m}_{vent1}$ – mass flow entering CV in the upper layer, [kg/s]

$\dot{m}_{vent2}$ – mass flow entering CV in the lower layer, [kg/s]

At early stage of fire fuel mass loss $\dot{m}_f$ (conveyor mass loss) can be disregarded. However, the flame can be modeled approximately using The Simple Chemically Reacting System (SCRS). Generally:

$$1(kg)_{fuel} + s(kg)_{air} \rightarrow (1+s)(kg)_{product} \tag{3.3}$$

where: s – mass of air which is supplying the fire, (kg)

Already 's' is greater than '$s_{stoichiometric}$', therefore only fraction s_m is used in common.

$$s_m = s_{stoich} \cdot \dot{m}_f \tag{3.4}$$

where:

s_m – a fraction, [kg/s]

s_{stoich} – stoichiometric ratio of the air, (kg/kg).

The fraction s_m is calculated with the following formula (3.5):

$$s_m = \frac{\dot{Q}}{13{,}1 \cdot Y_{a,O2}} \tag{3.5}$$

where:

$\dot{Q}$ – heat release rate of the fire (it can be estimated for selected time with knowledge about fire load (equation 4.4), [kW],

$Y_{a,o2}$ – mass fraction of oxygen in air (approx. 0,232kg O_2/kg dry air).

According to Janssens 2000:

$$\dot{m}_e = K \cdot (1 - L_r)^{1/3} \cdot \dot{Q}^{1/3} \cdot \Delta Z_i^{5/3} \tag{3.6}$$

where:

K – a constant, (kg/kW$^{1/3}$m$^{5/3}$s), K=0,076, other values of K can be found in [Beyler 1986].

L_r – radiative loss fraction,

ΔZ_i – distance between the conveyor and bottom of upper layer, [m].

It is stated that:

- The energy used in the plume equations is a convective portion of the total heat release rate of the fire, not the total heat release rate (however, because of L_r radiative losses must be known)
- $\dot{Q}$ is assumed as 1/3 of total power.
- Fire is considered as a point, and the energy release is assumed as from the point, not from the area.
- Changes of density in the flow are considered small in comparison with the ambient density.
- Air entrainment into the plume of smoke is proportional to the velocity of the plume in each location.
- The profiles of vertical velocity and buoyancy force in horizontal sections are similar at all heights.

  Because of the plume shape is similar to a triangle, it is possible to calculate the "bottom virtual vertex" of the plume (equation [3.4] (Janssens 2000). (Bottom virtual vertex in fig. 3.1 is drawn at $\Delta Z_V = 0$, but this is only schematic overview).

$$\Delta Z_V = -1{,}02D + 0{,}083\dot{Q}^{2/5} \tag{3.7}$$

where:

ΔZ_V – distance between bottom virtual vertex and the point of fire, [m]

D – characteristic fuel dimension, [m].

Negative values of ΔZ_V indicate location above point of the fire, positive values indicate location below the point of the fire.

4. Conservation of energy

Conception of conservation of energy during the first stage of the fire of a conveyor belt in underground excavation is based on schematic equation (4.1) [Górniak, Szymczyk 1997]:

$$\Delta U_l = I_{in} - I_{out} + Q_{in} + L_{out} \tag{4.1}$$

It represents The First Law of Thermodynamics for opened systems, where:

ΔU_l – change of internal energy of selected layer, [J],

I_{in} – enthalpy flow in, [J],

I_{out} – enthalpy flow out, [J],

Q_{in} – heat transferred to selected layer, [J], (positive sign),

L_{out} – work done by a mixture of gases in selected layer, [J], (positive sign).

4.1. Radiation, convection and fire load

It may be assumed that during the fire of a conveyor belt in underground excavation at early stage heat transfer is considered as radiation (E) and convection (H_c) [Spearpoint 2008].

The cumulative radiant energy is defined as (4.2):

$$E = \int_0^t Q' dt = \varepsilon\sigma \int_0^t (T^4) dt \tag{4.2}$$

where:

E – cumulative radiant energy emitted by the surface over a period of time, (J/m^2)

Q' – radiant heat flux above the surface at any point of time, (W/m^2)

ε – emmissivity (0-white material, 1-black material),

σ – Stefan-Boltzman constant, [5,67x10^{-8} W/m^{2}K^4],

t – time from the start of the fire produced in a conveyor belt, [s],

T – temperature of an excavation, [K].

The rate of heat loss due to convection is given as (4.3) [Purkiss 1996]:

$$H_c = \dot{m}_f \cdot c_p \cdot (T_g - T_e) \tag{4.3}$$

where:

H_c – rate of heat loss due to convection, [W],

$\dot{m}_f$ – plume mass flow, [kg/s]

c_p – specific heat of mixture of gases being produced from burning belt conveyor, [J/kgK],

T_g – temperature of gases, [K],

T_e – temperature of excavation (the upper layer), (K).

It is easier to obtain total heat release during fire and divide it into selected parts of time dt.

It can be calculated according to Polish standard about fire load [PN-B-02852] and other international standards applied in other countries [Purkiss 1996]

In Poland fire load is defined as (4.4):

$$Q_f = \frac{\sum_{i=1}^{i=n} \left(H_{cvi} \cdot m_i \right)}{A} \tag{4.4}$$

where:

Q_f – fire load, [W/m^2],

H_{cvi} – calorific value of a material, [MJ/kg],

m_i – mass of a material, [kg],

A – surface of an excavation, [m^2].

The three elements mentioned (radiation, convection and fire load) can be written for selected CV in any excavation with conveyor belt for future consideration at early stage of the fire. However, as it is stated in chapter 2, during an early stage of a conveyor belt fire, radiation and convection can be simplified.

4.2. Temperature of the lower and the upper layer

The equation that gives the temperature change over time of the upper layer is defined in differential equation form as (4.5) [Fangrat 2001]:

$$\frac{dT_1}{dt} = \frac{T_1(c_p(T_1 - T_2)\sum \dot{m}_e - (1-d)\sum H_c - Q_1}{\rho_a T_a c_p A(H_{l2})} \tag{4.5}$$

where:

T_1 – temperature of the upper layer, (K)

T_2 – temperature of the lower layer, (K)

d – heat diffusivity, (m^2/s)

Q_1 – heat transported to the upper layer, mainly by convection (Hc) and radiation (E) from the fire, (W)

ρ_a – density of gases outside the CV, (kg/m^3)

T_a – temperature of gases outside the CV, (K)

A – area of the surface at floor of CV, (m^2)

H_{l2} – height of the lower layer (it is assumed and simplified that this is the level of smoke, too), (m).

Temperature of the lower layer is defined as (4.6) [Fangrat 2001]:

$$\frac{dT_2}{dt} = \frac{T_2}{H_{l2}}\left[\frac{c_p(T_a - T_2)\sum \dot{m}_{outc} + Q_2}{\rho_a T_a A c_p}\right] \tag{4.6}$$

where:

Q_2 – heat transported to the lower layer from the fire, mainly by convection (H_c) and radiation (E) from the fire, (W),

$\dot{m}_{outc}$ – mass of air stream which is not under influence of the fire, it is a part of $\dot{m}_{1out}$ and $\dot{m}_{2out}$, [kg/s].

4.3. Mass and volume of the smoke produced by the fire

According to references [Spearpoint 2008, Fitzgerald 2004], the mass of the smoke produced by the fire is defined as (4.7):

$$\dot{m}_s = 0{,}096 \cdot p \cdot \rho_{0} \cdot Y^{3/2}\left(g\frac{T_o}{T_f}\right)^{1/2} \tag{4.7}$$

where:

$\dot{m}_s$ – mass of smoke, [kg/s]

p – perimeter of the fire, [m]

Y – distance between the floor and the level of smoke (it is assumed, that for simplification this is the height of the lower layer, H_{l2}), [m]

ρ_0 – density of ambient air (1,22kg/m^3),

g – gravity acceleration, [m/s^2]

T_0 – temperature of ambient air (290K),

T_f – temperature of smoke in a plume (1100K).

According to previous assumptions (the fire treat as a point) – value 'p' is very close to zero. It gives a conclusion that at the first stage of fire of belt conveyor there will be lack of smoke production and detection can not be based on smoke detectors or other visual devices. Then - in order to obtain the volume of smoke it is necessary to connect the mass and the volume flow with application of density (4.8):

$$\dot{V} = \frac{\dot{m}}{\rho} \tag{4.8}$$

where:

$\dot{m}$ – mass flow, [kg/s]

$\dot{V}$ – volume flow, [m^3/s]

ρ – density, [kg/m^3].

The density of the smoke at temperature T is given by the following equation: (4.9):

$$\rho_s = 1{,}22\left(\frac{290}{T + 273}\right) \tag{4.9}$$

where: ρ_s – density of smoke, [kg/m^3].

Temperature of smoke at early stage of fire is low and it may be assumed almost equal to ambient temperature.

The information given above lead to energy conservation equations (4.10 and 4.11), and the idea of this complex phenomenon is presented in fig. 4.1.

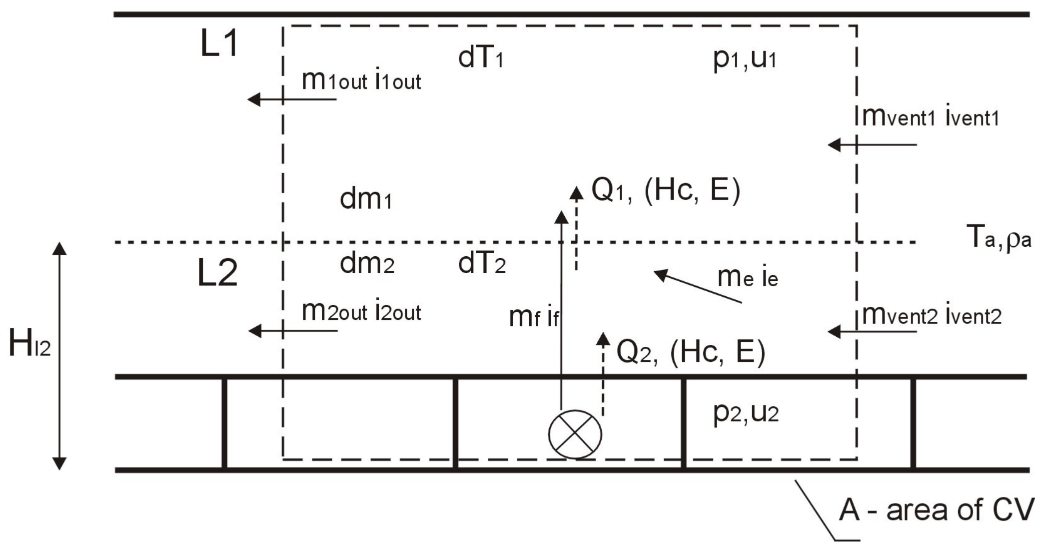

Fig. 4.1. Graphical representation of energy conservation during early stage of the conveyor belt fire in an underground excavation

Rys. 4.1. Graficzne przedstawienie zachowania energii podczas początkowej fazy pożaru przenośnika taśmowego w wyrobisku górniczym

Energy conservation for the lower layer is given as (4.10):

$$\frac{dm_2 u_2}{dt_2} = \dot{m}_{vent2} \cdot i_{vent2} - \dot{m}_{2out} \cdot i_{2out} - \dot{m}_e \cdot i_2 + \dot{Q}_2 - p_2 \frac{dV_2}{dt} \tag{4.10}$$

where: i_i – specific enthalpy of 'i' component, [J/kg].

Energy conservation for the upper layer is given as (4.11):

$$\frac{dm_1 u_1}{dt_1} = \dot{m}_f \cdot i_f - \dot{m}_{1out} \cdot i_{1out} + \dot{m}_e \cdot i_1 + \dot{Q}_1 - p_1 \frac{dV_1}{dt} \tag{4.11}$$

5. Conclusions

1. Layer model can be fit to mining conditions when necessary assumptions are considered. The example of the first stage of the conveyor belt fire in haulage excavation has been presented in the article.
2. Temperature of upper layer depends on temperature of lower layer. On the other hand – temperature of lower layer is strictly connected with fire parameters (mainly heat release which can be represented by fire load divided into time and related to entire area of an excavation) and ambient parameters (e.g. air velocity).
3. According to taken assumptions (the fire treat as a point) – perimeter of the fire '*p*' (equation 4.7) is very close to zero. It gives a conclusion that at the first stage of fire of belt conveyor there will be lack of smoke production and therefore - smoke detection can not be based on smoke detectors or other visual devices. Temperature detectors will be more sufficient.
4. Fire load calculations can be easy method to estimate heat emission for exogenous fires.

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Omówienie

W artykule omówiono przykład pożaru przenośnika taśmowego, będącego rezultatem prac Instytutu Eksploatacji Złóż w ramach Funduszu Węgla i Stali w programie badawczym EDAFFIC – "Early Detection And Fighting of Fires in Belt Conveyors", RFCR-CT-2008-00002, prowadzonym w latach 2008-2011.

Przedstawiono rozważania nad modelem warstwowym pożaru, który – mimo że jest stosowany najczęściej przy pożarach pomieszczeń – może być przystosowany do warunków pożaru egzogenicznego w wyrobisku górniczym. Model ten jest uproszczonym przypadkiem dyskusji nad początkową fazą rozwoju pożaru. Przy zastosowaniu równań zachowania masy i energii, znając podstawowe parametry pożaru, np. gęstość obciążenia ogniowego, można wyliczyć temperaturę warstw dolnej i górnej. Zastosowane równania i uproszczenia wskazują, że przy początkowej fazie pożaru, kiedy jest on traktowany punktowo, emisja dymu nie wystąpi bądź będzie ona na tyle znikoma, że w celu przeciwdziałania takim pożarom, należy stosować czujki temperatury, a reakcja czujek dymu może być znacznie spóźniona.

Wykazano, że powyżej wymieniony model pożaru warstwowego może być w pewnych warunkach stosowany w pierwszej fazie pożaru podziemnego, egzogenicznego. Istnieje możliwość wyznaczenia temperatur obu warstw na podstawie danych wejściowych, a moc całkowita pożaru może być wyliczona za pomocą pojęcia gęstości obciążenia ogniowego.