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NUMERICAL STUDY ON THERMAL ENVIRONMENT IN MINE GOB UNDER COAL OXIDATION CONDITION

BADANIA NUMERYCZNE ŚRODOWISKA TERMICZNEGO W ODPADACH KOPALNIANYCH W WARUNKACH UTLENIANIA WĘGLA

Abstract: The most feared of hazards in underground mines are those of fires and explosions. This study focuses on the temperature-rising process of residual coal under spontaneous combustion condition in coal mine gob. A numerical model has been established considering the chemical reaction, heat transfer and components seepage flow. The temperature distributions and maximum values for different positrons at various times have been calculated by using the coupled model. An experimental model has been also developed for model calibration. The validation indicates the numerical model is accurate and suitable for solving the temperature-rising problem in coalmines. The simulation results show that high temperature zone appears at the air intake roadway side in the gob and enlarging the ventilation flux increases the risk of self-ignition of coal. The research results can be used to predict the temperature-rising of coal spontaneous combustion and coal resources prevention.

Keywords: mine environment, residual coal, temperature rise process, spontaneous combustion

Introduction

Coal is the prime energy resource in most countries, 60% of them located in three countries: the United States, Russia, and China. Uncontrolled coal fires are a serious problem in many coal-producing countries and become an environmental and economic problem of international magnitude [1]. The incidence of mine fires appears not to be declining despite greatly improved methods of mine environmental design and hazard control. This is a consequence of two matters; first the growing variety of materials that are imported into modern mine workings, varying from resins and plastics to liquid fuels and hydraulic fluids. A second factor is the continuous increase in the employment of mechanized procedures, many of the machines involving flammable liquids and materials that can produce toxic fumes when over-heated. The enormous loss of life due to mine fires

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and explosions preoccupied the minds of mining engineers and scientists of the time. In recent decades, mine fires reemerged as a topic of pressing research need.

Although written accounts of coal fires date back to at least the time of Alexander the Great, the worldwide spread of coal fires has increased dramatically since the industrial revolution. Currently, thousands of coal fires are burning - some for centuries and many uncontrollably [2], with flames up to 20 m and temperatures exceeding 1000°C - from eastern Asia and northern China into the coal basins of Russia, Europe, Africa, north and south America, and Australia [3-5].

Coal fire is a global catastrophe, some of its prime impacts are [6]:

a) Emission of many toxic gases, such as carbon monoxide (CO), carbon dioxide (CO_2), sulfur oxides (SO_x), methane (CH_4), and nitrogen oxides (NO_x). Among these noxious gases, CO_2 and CH_4 contribute to global warming.
b) Geomorphic effects, include land subsidence, surface cracks, faults, and other geologic structures.
c) Temperature increment of surrounding areas, desiccation of forests, lowering of water quality.
d) Wasteful consumption of a potentially valuable resource.
e) Increment of production cost due to fire extinguishing and difficulties in mining operations.

Spontaneous combustion of coal is the main reason of coal fires [7]. The phenomenon of spontaneous combustion has been recognized since at least the seventeenth century. An early theory postulated that oxidation of pyretic material within coal provided centers of enhanced activity. This can play a part in the spontaneous combustion of timber or organic waste material underground but is unlikely to contribute significantly to the self-heating of coal or other minerals. Current researches on the initiation of self-heating showed that coal spontaneous combustion arose from the combined effects of coal and oxygen, including physical adsorption, chemical adsorption and chemical reaction. In recent years, work in this field was mainly focused on heat release, gas products, the functional groups and free radical changes of the spontaneous combustion of coal [8-14]. Meanwhile, high temperature combustion and the pyrolysis characteristics of coal are the research hotspots in the energy chemical industry, and the oxygen-enriched combustion (oxygen concentration > 21%) characteristics of coal such as initial reaction temperature, ignition temperature, combustion reaction rate and their relationships with the oxygen concentration have been studied intensively [15-22].

However, the research results were mainly for mechanisms of spontaneous combustion of coal, and may not have been applicable directly to the evolution of thermal environment in coal mines because the susceptibility to spontaneous combustion depends not only upon the material but also its physical state as well as the psychometric condition and migration paths of the leakage airflows.

The development of self-heating requires the large surface area of crushed material, combined with a slow migration of air through that material. Hence, spontaneous combustion of coal underground takes place mainly in the gob areas, caved zones, crushed pillar edges [23], and occurs through a complex system of thermal, hydraulic, chemical, and mechanical processes [24]. Many efforts have been undertaken to understand dynamic processes involved in coal combustion, which are of physical and chemical nature [25].

Despite their potential for environmental impacts, coal fires are not accurately quantified in terms of temperature predictions [26].

To study the thermal risk caused by residual coal oxidation in gob, this paper develops an effective simulation model of temperature-rising process due to the spontaneous combustion. The numerical model is presented combined with diffusion, reaction and heat transfer equations. The temperature distributions of different areas in gob and their accelerated variation process with time are discussed firstly, and then the effects of different ventilation conditions on spontaneous combustion of residual coal are analyzed through numerical simulation.

Theory

Mechanisms of spontaneous combustion in coal

Although spontaneous combustion can occur in crushed or caved sulphide minerals and in heavily timbered areas within metal mines, the problem is most common in coal mines. The progressive stages of spontaneous combustion appear to be complex and not yet fully understood. Generally, the oxidation processes of coal occur in following four stages:

a) Physical adsorption of oxygen commences at a temperature of about –80ºC and is reversible but diminishes rapidly as the temperature increases to become negligible beyond 30 to 50ºC. The process of adsorption produces heat as a by-product of the modified surface energy of the material. This causes the initial rise in temperature.
b) Chemical absorption becomes significant at about 5ºC. This progressively causes the formation of unstable compounds of hydrocarbons and oxygen known as peroxy-complexes.
c) At a temperature which appears to approximate to the self-heating temperature of the coal, the peroxy-complexes decompose at an accelerating rate to provide additional oxygen for the further stages of oxidation. This occurs within the range of approximately 50 to 120ºC with a typical value of 70ºC. At higher temperatures, the peroxy-complexes decompose at a greater rate than they are formed and the gaseous products of chemical reaction appear - in particular, carbon monoxide, carbon dioxide, water vapor, and the oxalic acids, aromatic acids and unsaturated hydrocarbons that give the characteristic odour of gob stink.
d) When the temperature exceeds some 150ºC, the combustion process accelerates rapidly. Incineration of the coal occurs with escalating emissions of the gaseous products of combustion.

In brief, the chemical reaction between coal and oxygen is complex. The following three types of processes are believed to occur [27]: a) physical adsorption; b) chemical adsorption, which leads to the formation of coal-oxygen complexes and oxygenated carbon species; and c) oxidation, in which the coal and oxygen react and release gaseous products such as carbon monoxide (CO), carbon dioxide (CO_2), and water vapor (H_2O). Of the above processes, coal spontaneous combustion can be regarded as an exothermic reaction of coal and oxygen at low concentration:

$$\text{Coal} + \text{O}_2 \rightarrow \text{Solid Products} + \text{Exhausted Gases} + \text{Heat Release} \quad (1)$$

The reaction rate is predominated by the concentration of oxygen in the fire front area, which is mainly supplied by air convective transport through the fractures of overlying

rocks. According to the Arrhenius equation, coal reaction rate ω at low temperatures can be expressed by the following equation:

$$\omega = -C_C C_{O_2} A_0 e^{-E/RT} \tag{2}$$

Where C_C, C_{O_2} are the coal and oxygen concentrations, E is the activation energy which for different coals can vary from 12-95 kJ/mol, A_0 is the pre-exponential factor which is typically between 1 and 7×10^5 $m^3kg^{-1}s^{-1}$ and depends on the coal rank and measurement method, R is the gas constant and R = 8.314 $Jmol^{-1}K^{-1}$, T is the absolute temperature.

Mathematical model

The mathematical model for temperature distribution in the mine gob is developed along with specific boundary conditions and initial conditions. The following equations apply to the coupled diffusion-reaction-heat transfer phenomenon in gob.

The energy transport equation is formulated under the assumption of thermal equilibrium between the solid matrix and gas. Thermal energy released by coal spontaneous combustion is transported through three mechanisms: conduction through surrounding rocks, convection through gas transport in the rocks and heat radiation due to high combustion temperatures. Because coal oxidation is an exothermic process, the link between heat production and oxygen consumption must be considered. Therefore, the mathematical model should contain energy conservation equations such as:

$$C_C Cp \frac{\partial T}{\partial t} + \nabla \cdot q_h - Q = 0 \tag{3}$$

Where t is the time, Cp is the specific heat capacity of coal, T is the thermodynamic temperature, q_h is total heat flux and Q is the source term which describes the heat release capacity of coal. The energy source term is directly proportional to calorific value ΔH through coal consumption rate ω.

The heat flux consists of three parts: heat conduction, convection and radiation, which can be formulated:

$$q_h = q_{cd} + q_{cv} + q_r \tag{4}$$

The conduction heat flux is given according to Fourier's law:

$$q_{cd} = -\lambda \nabla T \tag{5}$$

The convection heat flux q_{CV} through gas transport in the gob can be formulated:

$$q_{cv} = C_f Cd^f \vec{V} T \tag{6}$$

where λ is the thermal conductivity of coal in the gob, C_f is gas concentration, Cd^f is convective heat transfer coefficient and $\vec{V}$ is seepage velocity in the gob which is determined by the gob permeability and oxygen distribution. Gob permeability is largely affected by the distribution of pressure in the gob. The permeability at the edge of the gob is significantly different to that in the middle, and the permeability in these areas can range from 10^{-2} m^2 to 10^{-7} m^2. In the simulation in the present study, gob permeability was varied from 10^{-2} m^2 to 10^{-9} m^2, and the permeability was expressed by a hyperbolic tangent function. Oxygen concentration has great influence on the thermodynamic properties of the

oxidation and combustion of coal [28]. In this study, the seepage velocity is assumed as a function of difference value of oxygen concentration from contiguous areas in the gob.

The radiation heat flux q_r is determined by *radiative transfer equation* (RTE). Many methods have been established and applied to solve RTE equation successfully [29-36]. Here, considering the efficiency of coupled computation, a relatively simple 4-flux model is involved for 2-D simulation. The radiation heat flux can be written as:

$$-\nabla \cdot q_r = 2\kappa\left(q_{rx} + q_{ry} - 2E_b\right) + \sigma\left(q_{rx} + q_{ry}\right) \tag{7}$$

where κ, σ are absorption and scattering coefficient, E_b is blackbody radiation energy, q_{rx}, q_{ry} are component of radiation heat flux in x and y direction which can be solved by following equations:

$$\frac{\partial}{\partial x}\left[\frac{1}{\kappa+\sigma}\frac{\partial q_{rx}}{\partial x}\right] = \kappa\left(q_{rx} - E_b\right) + \frac{\sigma}{2}\left(2q_{rx} - q_{ry}\right) \tag{8}$$

$$\frac{\partial}{\partial y}\left[\frac{1}{\kappa+\sigma}\frac{\partial q_{rx}}{\partial y}\right] = \kappa\left(q_{ry} - E_b\right) + \frac{\sigma}{2}\left(2q_{ry} - q_{rx}\right) \tag{9}$$

Model setup

Configuration of simulation

In this study, the model is based on a workface in Dafosi coalmine in China, which has a U-type ventilation mode. Figure 1 shows the layout for the CFD model based on the Dafosi coalmine workface. The intake airflow and return airflow are on the top and bottom, respectively, of the front of this model. The length of the workface in the model was 200 m, and the distance from the starting point of the longwall to the workface was 500 m. The workface in this area is ventilated at 1400 m^3/min with fresh air with the following composition (percentage by volume): oxygen (20.7%), and nitrogen (78.6%).

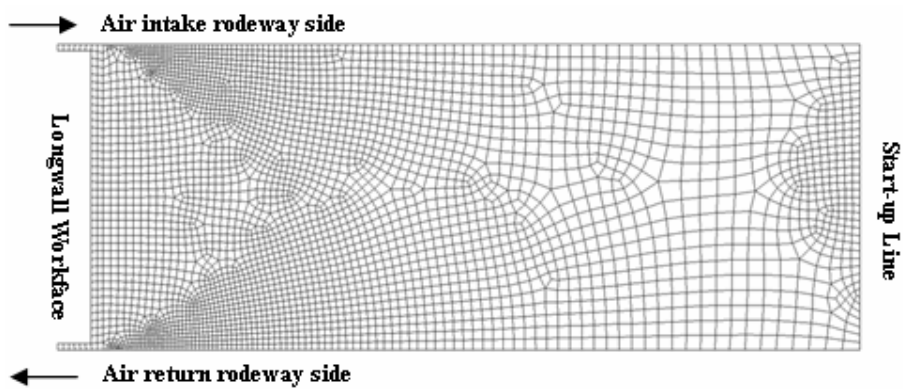

Fig. 1. CFD model geometry and computational grid of a gob

The model was meshed using an unstructured grid containing about 3518 cells, 7190 faces and 3673 nodes. For the model to converge easily during the solving process,

the mesh was increased around where the temperature is higher than 70ºC. In this study, the energy transport equation and radiation equations are derivated into discrete equations by finite difference method, and then solved by Tridiagonal matrix method. The coal spontaneous combustion model has also been implemented in the code through a surface element which enables to impose thermal flux produced from coal combustion for heat transport. During the implementation, a sub-iteration technique has been adopted for correctly capturing the high rising rate of the temperature, resulting in small time step of iteration. In addition, the modified surface element is also capable of predicting the concentration evolutions for exhausted gases and solid products.

Boundary and initial conditions were set as follows. At boundaries of air intake roadway side, return roadway side and start-up line, Neumann boundary condition apply for all temperatures, that means the wall temperatures are constant and defined as 300K. At boundary of longwall workface, convection boundary condition apply for the temperature because the continuing ventilation through the workface. The initial temperature distribution in the gob is set to 300 K everywhere.

Parameters used for the simulation are summarized in Table 1.

Table 1

Parameters for the example simulation

Description	Parameter	Unit	Value
activation energy	E	$[Jmol^{-1}]$	0.9×10^{4}
pre-exponential factor	A_0	$[m^3kg^{-1}s^{-1}]$	5×10^{5}
specific heat capacity	Cp	$[Jm^{-3}K^{-1}]$	4×10^{5}
calorific value	ΔH	$[Jkg^{-1}]$	1.2×10^{6}
thermal conductivity of coal	λ	$[Wm^{-1}K^{-1}]$	0.2
convective heat transfer coefficient	Cd^{f}	$[Jkg^{-1}K^{-1}]$	1000
absorption coefficient	κ	$[m^{-1}]$	10
scattering coefficient	σ	$[m^{-1}]$	10

In-situ measurement

For calibration and to validate the simulation results, samples were collected from the gob in an actual coal mine and analyzed by thermal measurement to obtain the temperature data. To collect these samples, two collection tubes were placed in the gob behind the workface and scraper conveyor. One is located near the air intake roadway, and the other is set on the air return side.

Results

Model validation

Through the in-situ measurements in gob, the temperature data are collected behind the workface on both the air intake and return roadway side as shown in Figure 2. By using the numerical method, the predicted temperature distributions from two sides are illustrated in Figure 3 respectively. It can be seen that the experimental and numerical results perform the similar trends. This suggests that the simulation can reflect the actual temperature in gob.

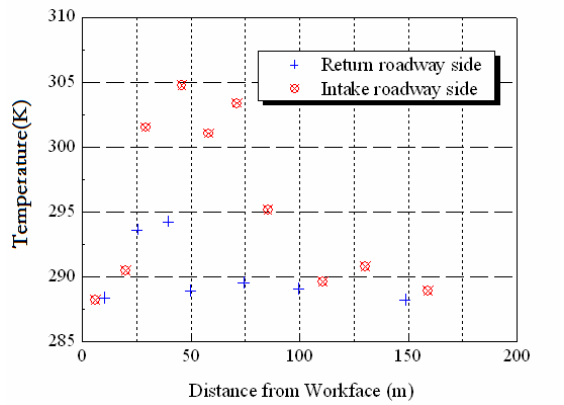

Fig. 2. Temperature distribution of different distances from the workface by experimental study

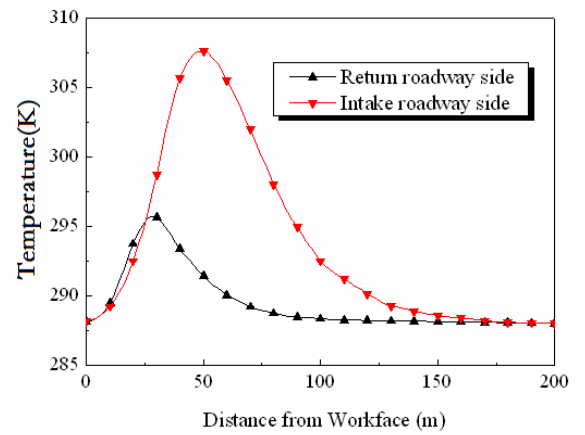

Fig. 3. Temperature distribution of different distances from the workface by simulation

Simulation results

According to Figure 3, the trends in temperature are very similar both on the intake and on the return side in the gob. Behind the long wall workface, the temperature rapidly rises to the peak value when the distance from workface increased, and then decreases slightly. The maximum value of temperature in the gob beside the air inlet was higher than that close the air return side.

The position of maximum temperature near the air intake side is about 55 m from the workface. On the air return side, the peak value occurs at the position of float coal dust 30 m from the workface. The simulation in this study also illustrates that the range of spontaneous combustion zone that directly relates to the temperature rising in the gob is not the same in different area.

The simulation results of temperature rise process in the gob are presented in Figure 4. It shows that along the intake boundary of working face, the acceleration rate of temperature rising is much higher than that close to the air return side.

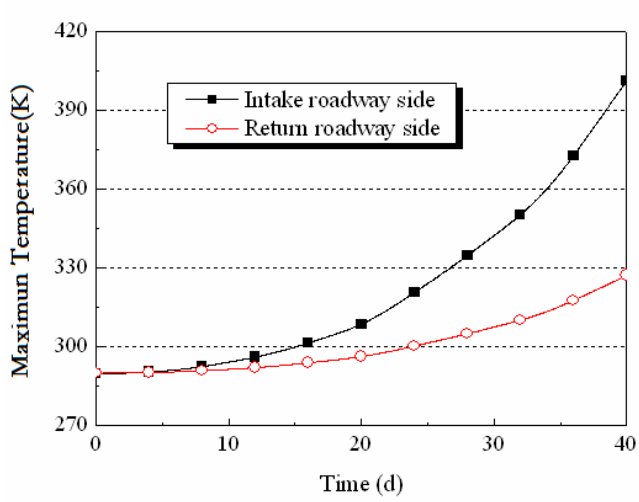

Fig. 4. Temperature rise process on intake and return roadway side in the gob

Discussions

In order to research the relationship between leakage and spontaneous combustion, the temperature distributions in different ventilation conditions are simulated. In case 1, the ventilation flux is assumed as 1400 m^3/min and it enlarges to 2000 m^3/min in case 2. As shown in Figures 5 and 6, different ventilation flux makes for great differences in temperature rising and spontaneous combustion results in gob. Increasing the drainage flux increased the leakage from the working face to the gob, which provided sufficient oxygen in the gob and enlarged the scope of spontaneous combustion and oxidation possibilities, as well as the fire zone. Therefore, the risk of spontaneous combustion is greatly enhanced.

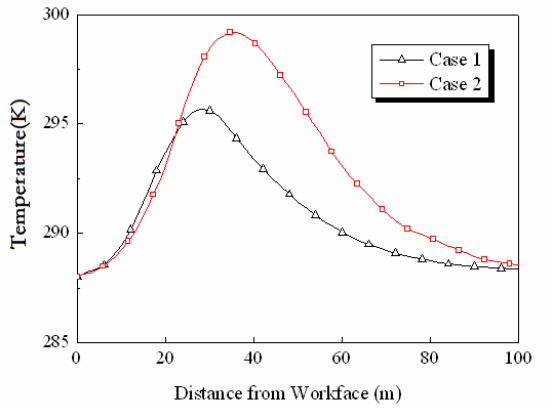

Fig. 5. Temperature distributions on the air return side with different ventilation flux

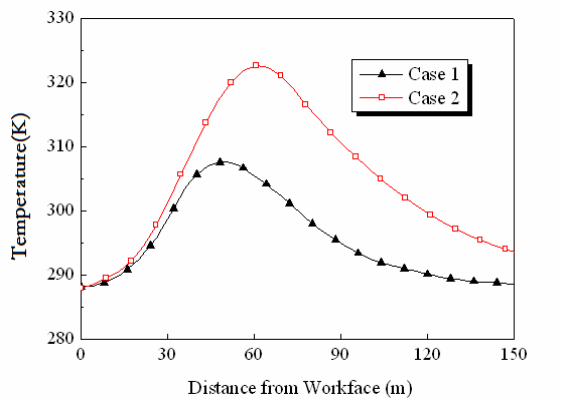

Fig. 6. Temperature distributions on the air intake side with different ventilation flux

Figure 7 shows the rising process of maximum temperature in gob with different ventilation flux. Comparing these two curves, the increased in-leakage airflow across the whole gob, supplies oxygen directly to the deep zone, where the oxygen is fully consumed. When ventilation flux increases, the spontaneous combustion period is shorter and the fire area is larger. Therefore, ventilation flux must be controlled and should be not too large.

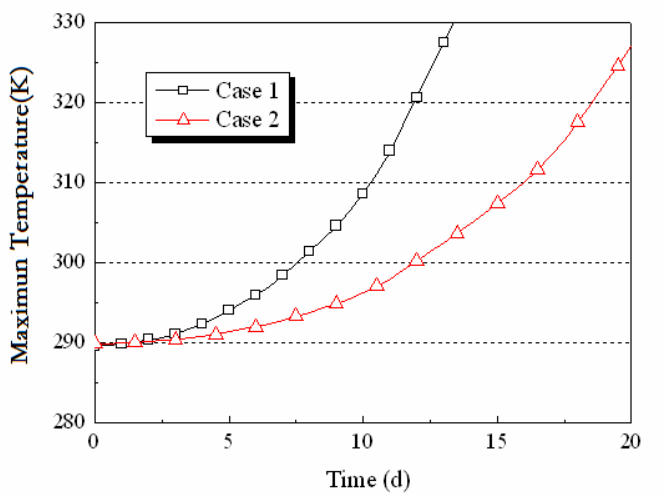

Fig. 7. Rising process of maximum temperature in the gob with different ventilation flux

Conclusion

In order to simulate the temperature rise process in gob under spontaneous combustion conditions, numerical modeling is performed to solve the coupled flow, mass transfer and energy equations.

As a result, the simulated data are consistent with experimental results, which indicate that the model using in this paper is accurate and applicable. Moreover, according to the simulating results of temperature rising process in coal mine gob, high temperature zone appears on the air intake roadway side. The leakage flux from the working face to the gob increases as the ventilation flux increases, the effect has two aspects: it shortens the spontaneous combustion period and it enlarges the scale of spontaneous combustion, which increases the risk of spontaneous combustion of residual coal in the gob.

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BADANIA NUMERYCZNE ŚRODOWISKA TERMICZNEGO W ODPADACH KOPALNIANYCH W WARUNKACH UTLENIANIA WĘGLA

Abstrakt: Pożary i wybuchy stanowią największe zagrożenia w kopalniach. Opisane w pracy badania dotyczą procesów powodujących wzrost temperatury resztkowego węgla, doprowadzający do jego samozapłonu, w odpadach z kopalni. Model numeryczny sformułowano, biorąc pod uwagę reakcje chemiczne, wymianę ciepła i przepływy składników. Rozkłady temperatury i maksymalne wartości w różnych położeniach i w różnych czasach zostały obliczone z użyciem modelu sprzężonego. Do kalibracji został również opracowany model doświadczalny. Walidacja wykazała, że model numeryczny jest dokładny i odpowiedni do rozwiązania problemu wzrostu temperatury w kopalniach węgla. Wyniki symulacji wskazują, że strefa podwyższonej temperatury

pojawia się na szlakach wlotu powietrza do materiału i zwiększenie strumienia wentylującego zwiększa ryzyko samozapłonu węgla. Wyniki badań mogą być wykorzystane do przewidywania wzrostu temperatury grożącego samozapłonem węgla oraz do ochrony jego zasobów.

Słowa kluczowe: środowisko kopalni, pozostałości węgla, proces wzrostu temperatury, samozapłon