Gob Spontaneous Combustion in a Fully Mechanized Long-wall Top-Coal Caving Face

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ABSTRACT

Geological conditions allow, underground coal mines in China tend to use comprehensively mechanized roof-coal caving technique in an effort to gain a higher degree of mechanization at coal faces as well as higher coal production rates. As a face advances, a large amount of coal will be left behind in its gob area which may experience a self-enhancing process of coal oxidation and heat accumulation, ultimately leading to open fire. Such a self-enhancing coal spontaneous combustion process is a significantly impeding mine safety and productivity. A sound mathematical model is an important step to predict the probability of spontaneous combustion so that measures against coal self-heating can be adopted in time and at comparatively low cost. This paper analyzes main factors in coal spontaneous combustion process and proposes a mathematical model to describe the dynamic process of coal self-heating in the gob. This model has been applied to a coal production face in *Datong Coal Region* in Shangdong Province to satisfactorily predict the spontaneous combustion probability.

KEYWORDS

Fully Mechanized Long-Wall, Top-Coal Caving Face, Gob, Mathematical Model, Spontaneous Combustion, and Face Advancing.

INTRODUCTION

With the current steady increase in world coal production (3.6% annual growth) and the increasing depth at which coal must be recovered, more underground mines will be developed. Currently 96% of the total coal production comes from underground mines in China (Fan, 1997). Wherever geological conditions allow, underground coal mines in China tend to adopt fully mechanized roof-coal caving technique in an effort to gain a higher degree of mechanization at coal faces as well as higher coal production rates. As a face advances, a large amount of coal will be left behind its gob area which may experience a self-enhancing process of coal oxidation and heat accumulation, ultimately leading to open fire. Such a self-enhancing coal spontaneous combustion process will significantly hinder mine safety and productivity. In China, many mine fires in recent years were caused by spontaneous combustion, resulting in financial losses and maybe even the mine shutdown. A sound mathematical tool is required to predict spontaneous combustion susceptibility so that proper fire-fighting measures can be adopted quickly with comparatively low cost.

FACTORS THAT INFLUENCE SPONTANEOUS COMBUSTION

Theoretically, for a spontaneous combustion to occur, the following three conditions must exist at the same time:

- The presence of crushed coal that is susceptible to low temperature oxidation.
- There must be air flowing into the place where loose-coal is accumulated.
- The possibility of heat accumulation during the reaction of coal oxidation.

However, actual conditions in and around mining faces can vary greatly. Many geological and mining factors such as: Thickness and dipping angle of coal seam, initial temperature of coal, humidity, faults, rock pressure, face advance rate, mining methods, ventilation system, and so on, all affect the process of spontaneous combustion of coal in the gob. Based on the analysis of main influencing factors in the process of coal spontaneous combustion (Xu., *et al.,* 1997), a mathematical model for the dynamic process of coal self-heating in the gob was developed.

MATHMETICAL MODEL

Properties of Coal Oxidation

Spontaneous combustion of coal results from the exothermic reaction of coal and oxygen. Based on the chemical dynamics, the reaction rate of coal oxidation is given as follows,

$$V(T) = A_1 \cdot C \cdot \exp[-E/(R \cdot T)] \tag{1}$$

where A_1 is general influence coefficient (for example coal size, porousity); R is general gas constant; E is active energy of coal; T is coal temperature; C is concentration of coal.

On the other hand, the exothermicity of coal is directly proportion to the reaction rate of coal oxidation $V(T)$, *viz*

$$q = H(T) \cdot V(T) \tag{2}$$

where $H(T)$ denotes intensity of exothermicity for unit volume of oxygen.

So $q(T) = A_2 \cdot C \cdot \exp[-E/(R \cdot T)]$ (3)

Where $A_2 = A_1 \cdot H(T)$

Distributing Model of Oxygen in Gob

- Air-Leakage Flow Model

Because velocity of air-leakage is slow, in gob, the equation of flow is concluded according to Dacy's principle.

$$\begin{cases} \overline{Q}_x = -K_x \dfrac{\partial P}{\partial x} \\ \overline{Q}_y = -K_y \dfrac{\partial P}{\partial y} \\ \overline{Q}_z = -K_z \dfrac{\partial P}{\partial z} \end{cases} \tag{4}$$

where $\overline{Q}_x, \overline{Q}_y, \overline{Q}_z$ denotes intensity component of air leakage on x, y, z respectively P is pressure difference, K_i is permeability coefficient, i denotes coordinates x, y, z. On the basis of continuity equation, the flow equation of air in the gob is

$$\frac{\partial}{\partial x}(K_x \frac{\partial P}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial P}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial P}{\partial z}) = r \tag{5}$$

where r denotes source of air in the gob.
as $r = 0$, the above equation becomes

$$\frac{\partial}{\partial x}(K_x \frac{\partial P}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial P}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial P}{\partial z}) = 0 \tag{6}$$

- Permeability model of oxygen in the gob

The factors that affect oxygen concentration, are mainly oxidation of coal, diffusion of oxygen, convection transfer of gas, and diluting by CH_4, CO, CO_2, H_2O. If the unsteady item is omit, the oxygen transfer equation is

$$\frac{dC}{d\tau} + \frac{\overline{Q}_x}{n}\frac{dC}{dx} + \frac{\overline{Q}_y}{n}\frac{dC}{dy} + \frac{\overline{Q}_z}{n}\frac{dC}{dz} = D_x \frac{d^2C}{dx^2} + D_y \frac{d^2C}{dy^2} + D_z \frac{d^2C}{dz^2} - V(T) \tag{7}$$

where D_x, D_y, D_z is diffusive coefficient on *x,y,z*.

Boundary conditions,
First kind :

$$C|_{y=0} = C_0;\ C|_{z=0} = C_0;\ C|_{x=L} = 0;\ C|_{y=L} = 0;\ C|_{z=L} = 0$$

Second kind: $\frac{dC}{dx}|_{x=0} = 0$

Coal Temperature Model in the Gob

On the basis of energy conversation law, the temperature balance equation is concluded as follows,

$$\rho_e C_e \frac{\partial T}{\partial t} = q_{(T)} + \lambda_e (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) - \rho_g C_g (\overline{Q}_x \frac{\partial T}{\partial x} + \overline{Q}_y \frac{\partial T}{\partial y} + \overline{Q}_z \frac{\partial T}{\partial z}) \tag{8}$$

where

ρ_e: equivalent general density; $\rho_e = \rho_g n + \rho_m (1-n)$;

C_e: equivalent general thermal capacity, and can be calculated as $C_e = C_g n + C_m (1-n)$;

λe: coal equivalent conductivity coefficient, which can be calculate as: $\lambda_e = (1-n)\lambda_m + n\lambda_g$;

subscripts *m and g* denote coal and gas respectively.

Initial the conditions, $T|_{\tau=0} = T_w$
Boundary conditions, of first kind:

$$T|_{x=0} = T_w;\ T|_{y=0} = T_w;\ T|_{x=L} = T_w;\ T|_{y=L} = T_w;\ T|_{z=L} = T_w$$

of third kind: $-\lambda_e \frac{dT}{dx}|_{x=0} = h(T - T_g)$

where T_w is temperature of ambient rock, C; T_a is temperature of air C; h is convection exchange heat coefficient.

INFLUENCE OF FACE ADVANCE

A fixed and a dynamic reference frames are set up (see Figure 1). As face advancing with the speed $u(t)$, the value of x of one point A in the coordinate system xoy is changed to

$$x = u(t)\cdot t - x' \tag{9}$$

where t is the time of the face advancing; x' is a value in the coordinate system $x'oy'$.

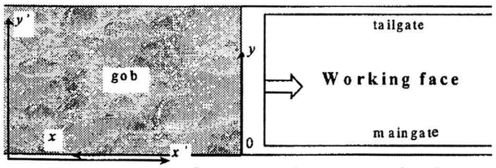

Figure 1. Schematic diagram of gob.

On the assumption that the profile of intensity of air-leakage is independence on the speed of face advance in the gob, the intensity of air-leakage $\overline{Q}(x',y,z)$ at any point in the coordinate system $x'oy'$ is changed to $\overline{Q}(u(t)\cdot t - x',y,z)$ in the coordinate system xoy, with the face advancing. The other variables ϕ, such as temperature T, concentration of oxygen C, and so on are changeless.

DETERMINATION OF PHYSICAL PARAMETERS

Permeability

According to literature[1] the permeability coefficient K is

$$K = \frac{k}{\mu} \tag{10}$$

where k is the permeability of coal, μ is viscosity coefficient of air, Pa.s.

The permeability k is correlative with porousity n. According to former soviet scholars' experiment results[2], the relation of k and n is

$$k = a_1 \exp(b_1 n) \tag{11}$$

where a_1 and b_1 is experience coefficient (where n has a value of 0.25~0.5, $a_1 = 1.448\times10^{-27}\mu$; $b_1 = 112.998$)

Diffusive Coefficient of Oxygen

The diffusive coefficient of oxygen in the gob is

$$D_i = \delta \frac{1}{\frac{1}{D_{O_2}} + \frac{1}{D_k}} \tag{12}$$

where i denotes coordinates x,y,z; D_{O_2} is the normal diffusion coefficient of oxygen, 0.2m^2/s; D_k is Kundsen diffusion coefficient which is correlative with average speed of molecule (temperature T) and hole diameter a in gob, namely, $D_k = 3.068a(\frac{T}{M})^{1/2} = 17.15(T)^{1/2}a(m^2/s)$, M is the molecular weight; δ is the diffusion rate which is correlative with porousity n and shape factor ξ, i.e., $\delta = \frac{n}{\xi}$.

Air Leakage Intensity

Based on the cases of near and similar face, the air leakage intensity of new face is reduced[2].

$$\frac{\overline{Q}_1}{\overline{Q}_2} = R_{\varphi12}\cdot\left(\frac{Q_1}{Q_2}\right)^2 \tag{13}$$

where $Q_1,\overline{Q}_1$ and $Q_2,\overline{Q}_2$ is the air quantity and the air leakage intensity of the new face and its near face respectively, $R_{\varphi12}$ is the scale with the porosity.

Oxygen Concentration in the Gob

The profile of oxygen concentration is reduced with the intensity of air leakage in the gob[2].

$$C(x_2) = C(x_1)\cdot\exp\left[-\frac{V_0 n}{C_0\overline{Q}_1}(x_2 - x_1)\right] \tag{14}$$

where $C(x_2)$ and $C(x_1)$ is the concentration of oxygen at x_1 and x_2 in the gob respectively.

Other Parameters

Based on the results of experimental testing coal sample with the xk-3 units (Xu., 1996), which simulate the spontaneous combustion process of coal, the exothermicity ($q(T)$) of coal and the rate of oxygen consumption ($V(t)$) will be work out respectively. Then parameters can be fitted in Equations (1) and (3). The other values of physical parameters are showed in Table 1.

Table 1. Values of parameters in the numerical computation.

Parameters	Value
ρ_g	1.196×10^{-3} g/cm^3
c_g	1.01 J/(g.□);
λ_g	2.65×10^{-5} J/(cm^2 s□)
λ_g	2.457×10^{-4} J/(cm^2 s□)
ρ_m	1.4 g/cm^3
c_m	1.53 J/(g.□);
λ_m	1.17×10^{-3} J/(cm^2 s□)
D_i	0.28 cm^2/s

NUMERICAL RESULTS AND ANALYSIS

In terms of the actual cases and advance rate (Figure 2) of work face 8916 in *Datong* coal mine, we use above mathematical model equations to simulate the spontaneous combustion of the remained coal in the gob. Let it be supposed that the initial temperature is 20C and the coal thickness is 7 meters and the porosity is equate to 30% in the gob. The Figure 3 shows the results of computation for the work face 8916.

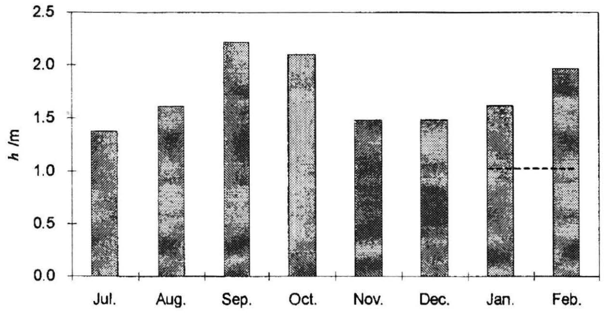

Figure 2. The speed of face 8916 advancing.

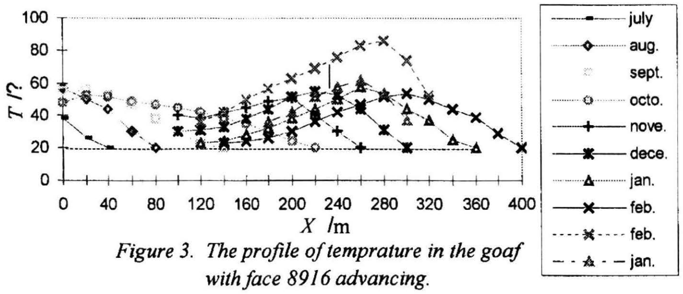

Figure 3. The profile of temprature in the goaf with face 8916 advancing.

It can be seen from Figure 3 that the highest temperature is about 54.3*C*, which is about 174.8meters apart from the face in Oct. The concentration of *CO* accordingly is about 50~100ppm in line with experimental results. As a result of the gas form the highest temperature point in the gob is diluted, we can estimate the concentration of *CO* on the upper of the face is about 30~60*ppm* which is corresponding with actual value measured.

On the initial stages of face advance, the temperature of the remained coal in the gob is increases with the face advance. The highest temperature point moved afterward. When it arrives the suffocation zone, the temperature is decreasing and the highest temperature point moves forward with the face advance. As the moving rate is slower than the face advance, the distance between the highest temperature point and the face become larger with the face advancing forward. If only the face actual advance rate is faster than a critical speed, the dynamic equilibrium when the highest temperature point moving is equated to the face advancing rate will reach. Conversely if the advance rate is slower than the critical speed, the highest temperature point will move foreword comparatively, and its temperature may increase in above 8 C. If any control measures won't be taken, we can predict that the gob of the face must be igniting after some days.

Result

- Based on the analysis of main factors in coal spontaneous combustion process, a mathematical model for the dynamic process of coal self-heating in the gob was put forward.
- According to the model of coal spontaneous combustion and the actual conditions of the face, the temperature and the gas concentrations profiles in the gob may be obtained with the face advancing.
- With respect to numerical result and analysis, one can obtain the estimation of the minimum safe advancing rate of the face and can predict the likelihood and susceptible areas of spontaneous combustion in the gob at any time.

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