Design of 3D Simulation System for Natural Ignition Law in Gob Area of Multi-source and Multi-sink

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Abstract. In order to comprehend the law of spontaneous combustion in "multi-source and multi-sink" goaf of coal mine, and to provide the basis for the prediction of early fire in goaf, the division of three zones of spontaneous combustion in goaf and the formulation of technical measures for fire prevention and extinguishing, a three-dimensional simulation system of spontaneous combustion law in goaf of "multi-source and multi-sink" coal mine is designed in this paper. The system uses energy conservation equation, Fick's law and mass conservation law to establish multi-source and multi-sink goaf fl ow field, oxygen concentration field, gas temperature field and caving coal and rock temperature field coupled mathematical model. The model is solved and programmed by using VB language mathematical model, which realizes the visual display of simulation results. The system is used to simulate the II929 mined-out area of Luling Mine, and good application results are obtained. The system has good operability and improves the calculation efficiency. It provides theoretical support for the prevention and control of spontaneous combustion in goaf of "multi-source and multi-sink" working face.

1. Introduction
The spontaneous combustion of coal in China is very serious, and the proportion of coal mines with natural fire hazard is large and the coverage is wide. In large and medium-sized coal mines, 72.9% of them are at serious risk of spontaneous fire. Due to the spontaneous combustion of coal seams, the annual loss of coal resources is about 200 million tons. Especially, there are many air leakage passages in the goaf, and the return air volume of the working face is much larger than that of the "multi-source and multi-sink" working face, when the residual coal in goaf has good conditions of heat storage and oxygen supply, it will spontaneously ignite. If it is not discovered in time and adopts safety technical measures, the equipment of the working face will be burnt down, and the mining face will not be able to continue. It may even cause major accidents such as gas explosion and cause great losses[1].

This paper designs a three-dimensional simulation system of natural ignition law in a multi-source and multi-sink goaf. It provides theoretical support for the prevention and control of spontaneous combustion in goaf of "multi-source and multi-sink" working face. Taking the II929 working face of Luling Mine as an example, the numerical simulation is carried out, and good results are obtained[2].

2. System Overall Design
In order to establish a three-dimensional simulation system for the natural ignition law of the multi-
source and multi-sink goaf, first we need to establish a relevant natural pyrotechnic mathematical model, then solve the mathematical model, and carry out the 3D simulation system program flow design, and finally complete the system interface and Programming design. The system design flow chart is shown in Figure 1:

3. Moving coordinate system and assumptions
As the mining face continues to advance, the boundaries of the mined areas are constantly changing and the spatial extent is expanding. For this reason, a moving coordinate system is introduced to transform the goaf that is continuously expanding into a steady-state, relatively fixed-area research object. As shown in Figure 2, taking the air inlet as the origin (o), the y-axis is set on the top line of the working surface, and the x-axis is along the goaf. The moving speed of the working surface can be approximated as a fixed constant[3].

As shown in Figure 3, the boundary near the working surface is Γ1, the upper and lower rows of coal pillars are Γ2, Γ3 boundaries, the top plate boundary is Γ5, the floor boundary is Γ6, and the deep boundary is Γ4. The boundary of the solid temperature field in the goaf is complicated. This is because the heat generated by the oxidation of the residual coal is not only transmitted within the actual boundary of the goaf, but also to the coal wall around the goaf, top and bottom. However the heat flux on the actual boundary of the goaf is undetermined[4]. Therefore, the actual boundary can not be used as the solution boundary of the solid temperature field, but should be extended to the protective pillars.

Figure 1. Flow chart of system design
Figure 2. Moving coordinates of goaf and boundary of temperature field of coal and rock
Figure 3. Boundary Conditions of Spontaneous Ignition in Goaf
on both sides, the boundary conditions on both sides are extrapolated to the position where the heat flux is almost zero, so the second boundary condition can be set.

4. Mathematical model

The natural ignition in goaf with” multi-source and multi-sink” is the result of interaction of pressure field, oxygen concentration field, gas and solid temperature field in goaf. The flow field equation in goaf is established by Darcy’s law and mass conservation law. The oxygen concentration field equation in goaf is established by Fick’s law and mass conservation law. The temperature field equation in goaf is established by Fourier’s law and energy conservation law[5]. The multi-field coupling mathematical model of spontaneous combustion in goaf is obtained, See Formula 1 Boundary conditions see Formula 2.

\[
\begin{align*}
\int_{\partial V} \frac{K}{g} \left( \frac{\partial \rho + \rho g h}{\partial n} \right) dS &= 0 \\
\int_{\partial V} n \kappa \frac{\partial C_o}{\partial n} dS - \int_{\partial V} C_o \frac{\partial \nu}{\partial n} dS - \int_{\partial V} u(t) dV &= 0 \\
\int_{\partial V} (1 - n) \lambda_e \frac{\partial T}{\partial n} dS - \int_{\partial V} K S_e (T_e - T_g) dV + \int_{\partial V} q(t) dV &= \int_{\partial V} (1 - n) \rho C_v \nu T \cos \alpha dS \\
\int_{\partial V} n \lambda_e \frac{\partial T}{\partial n} dS + \int_{\partial V} K S_e (T_e - T_g) dV - n \rho C_v \nu T \cos \alpha \int_{\partial V} \frac{\partial \nu}{\partial n} dS &= 0
\end{align*}
\]

\[
\begin{align*}
P_{V_1} &= p(x, y, z) \bigg|_{(x, y, z) \in \Gamma} ; \frac{\partial P}{\partial x} \bigg|_{r_1, r_2} = 0 ; \frac{\partial P}{\partial y} + \rho g \sin \alpha \bigg|_{r_1, r_2} = 0 \\
C_{o_1} \bigg|_{r_1} &= c(x, y, z) \bigg|_{(x, y, z) \in \Gamma} ; \frac{dC_o}{dx} \bigg|_{r_1, r_2} = 0 ; \frac{dC_o}{dy} \bigg|_{r_1, r_2} = 0 ; \frac{dC_o}{dz} \bigg|_{r_1, r_2} = 0 \\
t_{V_1} &= t(x, y, z) \bigg|_{(x, y, z) \in \Gamma} ; \frac{dt}{dx} \bigg|_{r_1, r_2} = 0 ; \frac{dt}{dy} \bigg|_{r_1, r_2} = 0 ; \frac{dt}{dz} \bigg|_{r_1, r_2} = 0 \\
t_{V_1} &= t(x, y, z) \bigg|_{(x, y, z) \in \Gamma} ; \frac{dt}{dx} \bigg|_{r_1, r_2} = 0 ; \frac{dt}{dy} \bigg|_{r_1, r_2} = 0 ; \frac{dt}{dz} \bigg|_{r_1, r_2} = 0
\end{align*}
\]

In Formula 2.K—permeability coefficient of porous media, m/s. pg—controlling gas density internal, kg/m^3. g—gravity acceleration, m/s^2. P—sum of static pressure and velocity pressure, Pa. α—dip angle of coal seam, degree. n—porosity of floating coal in goaf, %. k_a—diffusion coefficient constant of oxygen. u(t)—oxygen consumption per unit volume per unit volume, mol/(s·m^3). C_a—oxygen molar concentration, mol/m^3. λ_s—thermal conductivity of coal and rock in caving area, W/m·°C. Ke—coal-rock and gas convective heat transfer coefficient, J/(m^2·s·K). Tg—gas temperature. K. Ts—coal-rock temperature. K. ps—density of coal and rock, kg/m^3. Cs—specific heat capacity of coal and rock, KJ/(kg·K). q(t)—heat release of lost coal per unit time in control volume, KJ/(mol·s). ps—density of solid particles, kg/m^3. λ_g—gas thermal conductivity, W/m·°C. pg—density of gas in goaf, kg/m^3. Cg—specific heat capacity of gas, KJ/(kg·°C).

5. Model Solution and Programming

The finite volume method is used to solve the goaf spontaneous combustion model. Firstly, the solution range of the model is determined, the calculation area is meshed, and the model and its boundary conditions are discretized according to the finite volume method. The node equations of pressure, oxygen concentration and temperature are obtained[6]. Finally, the computer program is designed and compiled. The coupled equations of the equations are solved. Figure 4 is a flow chart of the program structure.
Figure 4. Program Flow Chart

VB6.0 is used to compile software startup interface, parameter setting interface and calculation interface, and in all aspects of the calculation program content programming. The system startup interface is shown in Figure 5[7].

Figure 5. System startup interface

Figure 6. Parameter Setting Interface Diagram

6. Simulation of II929 Working Face in Luling Mine

Luling mine 9# coal seam belongs to the coal seam with the property of easy natural ignition, the natural ignition period is 2-5 months, there are natural ignition hidden dangers. The working face at the later stage of stoping will be extended forward, and the return air roadway will stay in the goaf. However, the u-type ventilation mode cannot change the fact of air leakage in the goaf, and the working face has great gas control intensity, which is an objective and realistic condition that the
working face has the property of "multi-source and multi-sink".

According to the actual situation in the production process of working face of coal seam 1, the basic parameters related to spontaneous combustion in goaf are as follows:

1) The length of the working face is 120 m, the calculated depth of goaf is 250 m.
2) The thickness of residual coal in the goaf: the thickness of residual coal in the goaf is 0.3 m.
3) Air inlet temperature of the working face: the air inlet temperature of the working face is different due to seasonal changes. Combined with the wind temperature test results, 21.2 °C is taken, and the return air temperature is 24.6 °C on average. The original temperature of caving coal and rock was 28.6 °C.
4) The specific heat of residual coal is 1200 J/kg•℃, the density is 1410 kg/m³, thermal conductivity 1.275 w/m•℃; Roof density specific heat 1200 J/kg•℃, the density is 1410 kg/m³, thermal conductivity 1.589 w/m•℃.
5) The rate of oxygen consumption of the remaining coal: the rate of oxygen consumption obtained through the heating oxidation experiment, so see Formula 3.

\[
\begin{align*}
  u_0(t) &= 1.426 \times 10^{-5}t - 25.633 \times 10^{-5} & & t \leq 130 \\
  u_0(t) &= 6.591 \times 10^{-5}t - 694.13 \times 10^{-5} & & t > 130
\end{align*}
\]  

3) The exothermic intensity of the remaining coal: the exothermic intensity obtained through the heating and oxidation experiment, so see Formula 4[8].

\[
\begin{align*}
  q_0(t) &= 3.7927t - 89.023 & & t \leq 130 \\
  q_0(t) &= 22.000t - 2676.0 & & t > 130
\end{align*}
\]  

4) The ventilation resistance was 33.8 Pa. Due to serious air leakage, air inlet and air return on the working face are set at 500 m³/min and 800 m³/min respectively. The program running interface is shown in Figure 6.

Numerical simulation results is shown in Figure 7.

![Spatial Distribution of Pressure Field](image-a)
![Spatial Distribution of Oxygen Concentration Field](image-b)
![Spatial Distribution of Solid Temperature Field](image-c)
![Spatial Distribution of air Temperature Field](image-d)

**Figure 7.** Distribution of mined-out areas

According to figure 7(a), the pressure at the end of the goaf is the largest and there is air leakage from the goaf to the working face. Air leakage is so severe that it can easily cause spontaneous combustion of the remaining coal in the goaf.

According to figure 7(b), Owing to the existence of air leakage from goaf to working face, the oxygen concentration in the air inlet is high, which can not diffuse to the deep part of goaf. Near the roadway state, the spanning coal and rock are relatively loose and there are air leakage passages, so the oxygen concentration along the roadway state on both sides is relatively high. With the increase of oxygen concentration, the oxidation reaction of residual coal along the roadway-state area on both sides intensifies, and the heat generated transfers to the deep part of the goaf, while the deep caving coal and rock in the goaf is relatively dense, and the heat generated by the oxidation of coal and rock is easy to accumulate, which is more likely to lead to spontaneous combustion in the goaf.
According to figure 7(c) (d), the trend of solid temperature field is the same as that of gas temperature field. The high temperature area is higher at the air inlet, which is in a circular distribution, and the highest temperature is close to 70℃. In addition, narrow and long high temperature areas also appear near the coal pillars of protection, which are distributed along the roadway states on both sides. Therefore, it is very difficult to control the goaf spontaneous combustion.

7. Conclusion
In this paper, a three-dimensional simulation system is designed for the goaf spontaneous combustion law under the condition of “multiple sources and multiple sinks”, which conducts numerical simulation on the distribution rules of temperature field, oxygen concentration field and pressure field in goaf Luling coal mine II929. Compared with other similar simulation software, which has the following major improvements:

1) The mathematical model of spontaneous combustion in goaf with coupling of leakage flow field, the oxygen concentration field and temperature field in moving coordinate is established.
2) The flow field model is based on the non-reach west path, which more accurately reflects the flow movement rules in the actual goaf.
3) Grid encryption is carried out on the areas with large changes in the goaf, that is, the areas near the inlet and return air roadway and the working face.
4) The finite volume method is more accurate than the finite element method;
5) The calculated data are identified by Tecplot and other post-processing software, which is easy to realize visualization.

The deficiency is that the system still needs post-processing software for image display, which will be gradually improved in the future software upgrade development.

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