CFD Numerical Modelling of Spontaneous Combustion of Loose Coal in High Caved Area of Underground Roadway

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Abstract. Coal fires are serious health and safety hazards throughout the world. In underground, coal spontaneous combustion process often starts with the inside of coal, which makes it difficult to determine the ignition point. For example, the coal fire happened in high caved area of roadway is often hard to be noticed. Once the smoke appears, it has already been late to take control measures. In this paper, Simulation analysis of microcirculation flow field velocity distribution, temperature distribution and the possible distribution of the coal spontaneous combustion zone are preformed which could provide a good scientific and reasonable understanding of the fire risk due to microcirculation in loose coal in underground roadway.

Keywords: Underground coal mine; Loose coal, Spontaneous combustion, Modelling

1. Introduction

Mine fire is one of fearful disasters concerning underground coal mines, which has been threatening a coal miners’ safety since the beginning of production. According to historical statistics [1,2], the nationalized coal mines of China subjected to the risk of spontaneous combustion account for 47% of all. Fire control is not only an important task of ventilation safety technology, but also plays a crucial role in the safety production of coal mines.

Essentially, the spontaneous combustion of coal [3,4] is the microcirculation process of heat balance between coal combustion and heat dissipation to the environment, and of the oxygen concentration balance between the oxygen supply of air leakage and the oxygen consumption of coal combustion. Low-temperature oxidation is one of the basic features of coal, but it is just the premise of spontaneous combustion. The decisive factor of spontaneous combustion is the stockpiling status of coal and the equilibrium state of heat and oxygen concentration in the microcirculation process. Based on actual observation, it has been detected that spontaneous combustion of coal is generally a bottom-up process, which makes it difficult to determine the ignition point. When the top coal of coal roadway is caved or the sidewall of coal roadway is fractured, spontaneous combustion of the top coal in the gate road and the loose coal on the sidewall may occur. According to the long-term practical observation in actual field condition, CO concentration and coal temperature will increase in a very short period of time after the top coal and sidewall of coal roadway is caved in driftage process [5-8]. The shortest period is about half a month after driftage, especially in the condition of deep mining. With the increasing earth pressure, the mining fracture increases accordingly. The thermal effect existing in the process of coal and rock caving gives rise to the possibility of spontaneous combustion of coal. Therefore, in this paper, temperature distribution and oxygen concentration in the coal seam of high caved area were studied through numerical simulation in order to discuss the microcirculation process of spontaneous combustion. In addition, at the same time, the actually measured seepage data
2. Airflow-related Parameter Calculation in the High Caved Area of a Coal Mine Test Field

Loose coals have different physical properties because of their different actual conditions, such as coal type and void ratio. In the actual calculation and prediction of coal spontaneous combustion in high caved area, it is necessary to consider the actual situation. Therefore, an actual simulation of underground spontaneous combustion in high caved area of a Coal Mine has been made. The test field is the connection roadway of eastern mining area. Temperature sensor and the sampling tube were buried under the coal in high caved area for temperature measurement and gas detection in the whole combustion process. Figure 1 is the profile map of the tunnel axis in the simulation of high caved area. The coal bed pitch is 15° and the tunnel length is 12. The test area is as shown in figure 1.

Figure 1. Diagram of Test Point Seepage in High Caved Area.

Table 1. Parameters used in the Mathematical Model.

| Parameter | Value         | Parameter | Value         |
|-----------|---------------|-----------|---------------|
| $\nu$     | 16.0×10^{-6} m^2/s | $D_m$     | 0.014 m       |
| $\lambda_m$ | 1.2×10^{-5} W/(m·K) | $\rho_\infty$ | 1.18 kg/m³ |
| $\rho_m$  | 1.4×10^3 kg/m³  | $\beta$   | 1.5           |
| $c_m$     | 1.53×10^{-3} J/(kg·K) | $\lambda_s$ | 0.26×10^{-3} W/(m·K) |
| $\rho_s$  | 1.01×10^3 kg/m³  | $c_s$     | J/(kg·K)      |

2.1. Physical Property Parameter of Loose Coal in High Caved Area of Coal Mine

The main parameters in numerical calculation are shown in table 1.

2.2. Void Ratio of Loose Coal in High Caved Area of Coal Mine

The Void ratio is a key parameter in deciding airflow motion in high caved area, which is directly related to the seepage intensity of airflow in high caved area. Besides, void ratio can affect the heat transfer performance of coal, so that it may also have great influence on the spontaneous combustion of coal. The void coefficient of high caved area is difficult to determine. Generally, physically similar material simulation experiment will be conducted to determine void coefficient. The similar experiment results show that the average void ratio is different in each district of high caved area. In
3. Numerical Simulation Study on Spontaneous Combustion of Loose Coal in High Caved Area in Coal Mine

3.1. Computational Domain and Mesh Generation of Numerical Calculation
In this numerical simulation, MATLAB was adopted to realize finite element solution. In order to simplify the study, the vertical change of the flow field was ignored to regard the airflow in high caved area as a two-dimensional seepage problem, so as to study the law of airflow in the computational domain of the test field as shown in figure 1. The seepage area is divided into a series of triangular element mesh and the mesh generation is as shown in figure 2, including 812 units and 456 nodes.

3.2. Calculation Results and Analysis
3.2.1. Temperature Distribution Law of Loose Coal in High Caved Area. The calculation conditions are: according to the measurements in laboratory experiment and field test, the heating intensity of coal \( q_0(T) \) is 216910 J/(h\cdot m^3), the initial temperature of coal in high caved area is 30°C, the temperature of fresh air in roadway is 30°C. The surface of the roadway takes the first-class boundary and the coboundary of loose coal takes the second-class boundary. The calculation results in 10 days and 30 days are as shown in figures 3-4.

It can be seen from the calculation results that, under the joint effects of coal oxidation and airflow dissipation, the coal will shape into several tiny areas in 10 days after coal oxidation which is at about 50°C. While in 30 days after coal oxidation, parts of the coal may reach up to 120°C. These data basically agree with the temperature distribution measured in test field of Coal Mine. It can be seen that spontaneous combustion in high caved area is the result of partial high temperature caused by coal oxidation. The high temperature of parts of the coal will result in airflow microcirculation and further lead to heat accumulation. According to air leakage theories mentioned above, the high-temperature zone at the ends of high caved area will be cooled down by the high seepage velocity, making it free from spontaneous combustion. The high-temperature zone at the middle part can be regarded as the main heat source area for spontaneous combustion.
3.2.2. Oxygen Concentration Distribution Law of Loose Coal in High Caved Area. The calculation conditions are: the initial oxygen concentration is the molarity of oxygen in fresh air - 9.375 mol/m³ (volume concentration is 21%). The temperature of fresh airflow is 30°C, and corresponding oxygen consumption rate of loose coal is \( V_0(T) = 0.68 \text{ mol/m}^3 \cdot \text{h} \). The roadway surface boundary takes the first-class boundary and the coboundary of loose coal takes the second-class boundary.

The calculation results of oxygen concentration distribution at t=10 hours/40 days are as shown in figures 5-6. Compared with temperature distribution, the higher-temperature zones come with lower oxygen concentration. This is because that the dramatic coal oxidization in the high-temperature zone will lead to high oxygen consumption rate. Besides, from the comparison of the two figures, it is clear that the temperature of the coal will be very high at 40 days after coal oxidation and the hot wind pressure will lead to the leap of air leakage. Oxygen supply of air leakage approximately equals to the oxygen consumption resulted from temperature increment. Therefore, there is no significant difference in oxygen concentration distribution in these two figures.

It can be seen in figure 6 that the molarity of oxygen in the high-temperature central air circulation area is 8.0 mol/m³ (volume concentration is 17.9%). This result is basically identical with the analytical results on field gas. At the same time, it also supports that the leap of air leakage caused by hot wind pressure supplies sufficient oxygen for spontaneous combustion.

Therefore, for spontaneous combustion of loose coal in high caved area of roadway, under the hot wind pressure, there exists microcirculation system of oxygen supplied by constant air leakage. With the spontaneous combustion of loose coal, on one hand, oxygen demanded for oxidation increases
with the increase of coal temperature; on the other hand, with the increase of coal temperature, hot wind pressure will result in increase of air leakage, leading to the increase of oxygen supply. The interaction of these two factors result in the decrease of oxygen concentration in loose coal, but it can still maintain the spontaneous combustion and keep the rising trend of loose coal. Therefore, the establishment and development of oxygen and heat microcirculation caused by the thermal oxidation of loose coal and the oxygen supply of air leakage will ultimately led to spontaneous combustion.

4. Conclusions
In this paper, the spontaneous combustion of loose coal in high caved area was solved through numerical method. The mechanism of spontaneous combustion of loose coal in high caved area was expounded theoretically. The main conclusions are as follows:

1) The spontaneous combustion of loose coal in high caved area is the comprehensive effect of multiple factors, which mainly depends on the heat released from coal oxidation, oxygen supply and heat accumulation environment. The spontaneous combustion model should make air leakage of loose coal, oxygen concentration and temperature distribution into consideration because this model is the nonlinear equation set established by the coupling of these factors.

2) The calculation results of temperature distribution show that the central coal will shape into several tiny areas at about 50℃ in 10 days after coal oxidation. While in 30 days after coal oxidation, the temperature of parts of the coal may reach up to 120℃. These data are basically identical to the field test in Coal Mine.

3) The oxygen consumption rate of coal oxidation is different in each area. In high-temperature area, oxygen consumption rate is relatively higher, so that results in the decrease of oxygen concentration.

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