DISTRIBUTION CHARACTERISTICS OF THE THREE ZONES OF SPONTANEOUS COMBUSTION IN THE GOAF OF THE WORKING FACE IN XIAOJIHAN MINE

by

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This study addresses the issue of spontaneous combustion in the goaf of the 11223 working face in Xiaojihan Mine. A 3-D model of the goaf was constructed using numerical simulation methods, incorporating actual working face parameters and the porous media fluid dynamics equations. The spatial distribution patterns of oxygen mass fraction, air-flow velocity, and turbulent kinetic energy in the goaf were simulated. The oxygen concentration distribution and air-flow characteristics in the goaf were analyzed, and the "three zones" of spontaneous combustion were delineated. The results indicate that the oxidation zone on the intake side ranges from 70-105 m (width of 35 m), the middle part of the goaf ranges from 40-75 m (width of 35 m), and the return side ranges from 10-25 m (width of 15 m), consistent with field measurements. The study reveals the non-uniform characteristics of the oxidation zone in the goaf, providing a theoretical basis for coal mine fire prevention and control.

Key words: *three-zone distribution, numerical simulation, oxygen concentration, air-flow field*

Introduction

Spontaneous combustion in the goaf is a significant hazard in coal mine safety production, primarily due to the dynamic balance between coal oxidation heat release and heat dissipation conditions. With the increasing depth of mining and the widespread application of fully mechanized caving technology, the risk of spontaneous combustion of residual coal in the goaf has significantly increased. Accurate delineation of the *three zone*s of spontaneous combustion (cooling zone, oxidation zone, and suffocation zone) is essential for effective prevention and control.

In recent years, numerous scholars have conducted extensive research on the delineation of spontaneous combustion zones in the goaf. Zhang *et al.* [1] used FLUENT software to study the air-flow field characteristics in the goaf, delineating the hazardous areas of spontaneous combustion and predicting coal spontaneous combustion. Zheng *et al.* [2] used COMSOL to establish a model of spontaneous combustion in the goaf, finding that air-flow velocity is a key factor affecting the location of high temperature zones within the goaf. Shi *et al.* [3] found that temperature changes in the goaf lag behind changes in air-flow velocity at the working face, with larger increases in air-flow velocity leading to greater temperature

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increases in the goaf. Mohalik *et al.* [4] used CFD methods to find that temperature increases in the goaf are related to the amount of residual coal and the area of roof collapse. Qiao *et al.* [5] conducted numerical simulations of the goaf and found that the direction of coal seam occurrence affects gas distribution within the goaf. Zhao *et al.* [6] studied the dynamic changes of spontaneous combustion zones in the goaf under different advancing distances. Zhang *et al.* [7] established a fracture-pore model of the goaf, revealing the gas migration characteristics and establishing a method to delineate spontaneous combustion zones based on oxygen concentration.

Existing research is mostly based on empirical formulas or simplified models, making it difficult to fully reflect the non-linear coupling mechanism of gas migration and oxidation reactions in the goaf. This study focuses on the 11223 working face in Xiaojihan Mine, using FLUENT software to simulate oxygen concentration distribution, air-flow velocity, and turbulent kinetic energy characteristics, quantitatively delineating the *three zones* of spontaneous combustion. The aim is to reveal the dynamic evolution of the oxidation zone in the goaf, providing a scientific basis for optimizing fire prevention and control technologies such as nitrogen injection and air leakage sealing, ensuring safe and efficient coal mining.

Working face overview

The 11223 working face in the 11th panel of Xiaojihan Mine is bounded to the north by the mine field boundary, to the south by the No. 2 auxiliary transportation roadway in the west wing of the No. 2 coal seam, to the west by the solid coal area of the 13203 working face, and to the east by the goaf of the 11221 working face. The working face is approximately 5044.7 m long and 315.5 m wide, with a mining area of about 1.5907 million m^2. The ground elevation of the working face ranges from 1215-1237 m, and the floor elevation ranges from 793-837 m. The terrain of the mining area is relatively flat, with a relative height difference of less than 40 m.

Simulation control equations

Numerical simulation calculates results under hypothetical conditions based on known physical or chemical parameters of materials and structures, satisfying corresponding equations. Gas-flow in the goaf must satisfy the conservation equations of mass, energy, momentum, and species [8].

The mass conservation equation for gas-flow in porous media [8]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho v_x)}{\partial x}+\frac{\partial(\rho v_y)}{\partial y}+\frac{\partial(\rho v_z)}{\partial z}=0 \tag{1}$$

where ρ is the gas density, t – the time, and v_i – the gas velocity vector ($i = x, y, z$).

To simplify the equation, the gradient operator is introduced:

$$\frac{\partial}{\partial x}i+\frac{\partial}{\partial y}j+\frac{\partial}{\partial z}k=\nabla \tag{2}$$

Substituting eq. (2) into eq. (1) simplifies:

$$\frac{\partial \rho}{\partial t}+\nabla(\rho v)=0 \tag{3}$$

For steady-state and incompressible flow, the fluid density is constant, and the mass conservation equation is [8]:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0 \tag{4}$$

Energy conversion in porous media fluid-flow satisfies [8]:

$$\begin{aligned}
\frac{\partial(\rho v_x)}{\partial t}+\nabla(\rho v v_x)&=-\frac{\partial p}{\partial x}+\nabla(\mu grudv_x)+S_{v_x}\\
\frac{\partial(\rho v_y)}{\partial t}+\nabla(\rho v v_y)&=-\frac{\partial p}{\partial y}+\nabla(\mu grudv_y)+S_{v_y}\\
\frac{\partial(\rho v_z)}{\partial t}+\nabla(\rho v v_z)&=-\frac{\partial p}{\partial z}+\nabla(\mu grudv_z)+S_{v_z}
\end{aligned} \tag{5}$$

where p is the pressure, μ – the dynamic viscosity, *grud* – the gradient, and S_v – thesource term ($i = x$, y, z).

Gas migration in the mining area involves energy conversion, primarily manifested in coal oxidation and heat dissipation processes [8]:

$$\frac{\partial(\rho T)}{\partial t}+\nabla(\rho v T)=\nabla\left(\frac{k_t}{c_p}grudT\right)+S_T \tag{6}$$

where T is the gas temperature, k_t – the solid thermal conductivity, c_p – the solid specific heat capacity, and S_T – the viscous dissipation term.

The species mass conservation equation:

$$\frac{\partial(\rho c_s)}{\partial t}+\nabla(\rho U c_s)=\nabla\left[D_s grud(\rho c_s)\right]+S_u+R_s \tag{7}$$

where c_s is the volume concentration of species, D_s – the diffusion coefficient of species, and S_u – the species generation rate per unit volume.

Numerical model establishment

Fluent software was used to simulate the gas-flow patterns in the goaf. The model was based on the actual dimensions of the 11223 fully mechanized caving face and goaf in Xiaojihan Mine. The intersection of the working face and goaf was selected as the co-ordinate origin. The X-axis was along the working face direction, with a length of 315 m. The Y-axis was along the working face width, with a width of 315.5 m. The Z-axis was upward along the working face, with a mining height plus caving height of 6.75 m. The intake airway was 6 m wide and 4 m high, and the return airway was 5.3 m wide and 3.8 m high, both 20 m long. The 3-D model of the fully mechanized caving face is shown in fig 1.

The computational domain was divided into three regions for meshing. The working face and intake/return airways were meshed with hexahedral (Hex) grids, with an interval size of 0.5 m. The caved zone of the goaf was meshed with Hex grids, with an interval size of 2 m. The fractured zone of the goaf was meshed with Hex grids, with an interval size of 10 m. The meshing diagram is shown in fig 2.

The model inlet air-flow velocity was 2.12 m/s, and the absolute gas emission rate during mining was 0.56 m^3 per minute. The goaf was set as a porous medium, with porosity and viscous resistance coefficients defined by UDF functions, imported into FLUENT for solution.

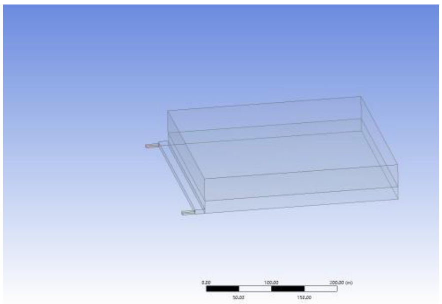

Figure 1. The 3-D model of the fully mechanized caving face

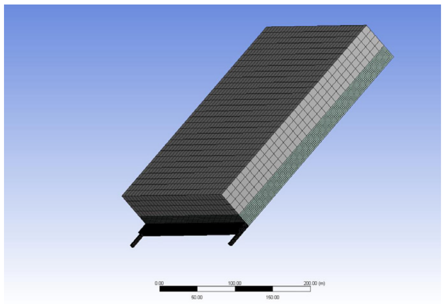

Figure 2. Meshing diagram of the goaf

Oxygen concentration and spontaneous combustion oxidation zone in the goaf

The O_2 mass fraction in the middle and intake/return sides of the goaf was extracted for analysis, as shown in fig 3. On the intake side, the O_2 mass fraction decreased to 18% at about 80 m into the goaf and to 8% at about 115 m. On the return side, the O_2 mass fraction decreased rapidly upon entering the goaf, reaching 18% at about 15 m and 8% at about 30 m. The O_2 mass fraction distribution in the goaf is non-uniform, with higher concentrations on the intake side than on the return side.

Figure 4 shows the variation of O_2 mass fraction on the intake, return sides, and middle of the goaf, with *three zones* delineated at O_2 mass fractions of 18% and 8%. Analysis of fig. 3 shows that the oxidation zone width decreases from the intake side to the return side. The oxidation zone on the intake side ranges from 80-115 m (width of 35 m), the middle part of the goaf ranges from 45-80 m (width of 35 m), and the return side ranges from 15-30 m (width of 15 m).

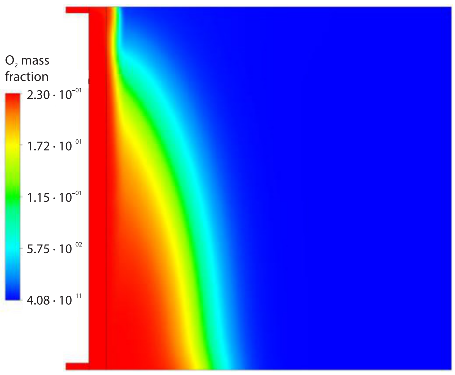

Figure 3. The O_2 mass fraction distribution in the goaf

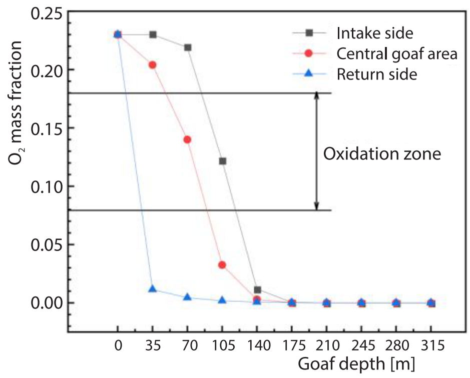

Figure 4. Variation of O_2 mass fraction on the intake, return sides, and middle of the goaf

Figure 5 shows the *X* and *Y* cross-sectional contours of O_2 mass fraction distribution in the goaf. The *X* cross-sectional contour shows that at the $x = 0$ goaf interface, the oxygen concentration distribution is the largest, existing across the entire working face dip and height. At the $x = 150$ m goaf interface, the oxygen concentration is higher only on the intake side, and the vertical height oxygen concentration is significantly reduced. At the $x = 200$ m goaf interface and beyond, there is almost no oxygen distribution in the goaf. The *Y* cross-sectional contour shows that the oxygen concentration range decreases along the dip.

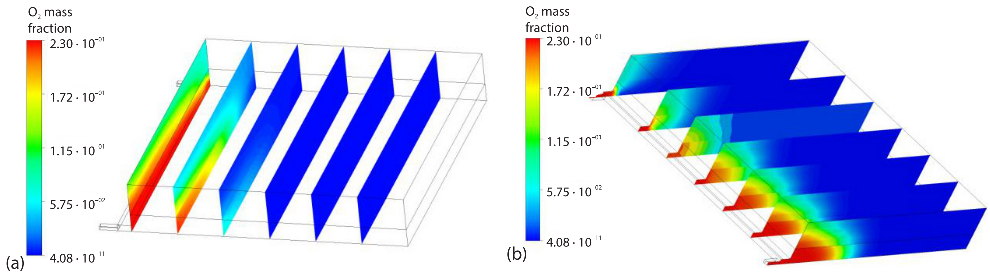

Figure 5. Cross-sectional contours of O_2 mass fraction distribution in the goaf; (a) overall *X* cross-sectional contour map and (b) overall *Y* cross-sectional contour map

Air-flow field analysis in the goaf

Based on the numerical simulation results, the air-flow velocity in the goaf is shown in fig. 6. The peak air-flow velocity is concentrated on the intake and return sides, with lower velocities in the middle of the goaf. As the goaf deepens, the compaction degree increases, leading to air-flow velocity loss and gradual decrease.

Figure 7 shows the turbulent kinetic energy distribution. The turbulent kinetic energy is higher near the working face and decreases as the goaf deepens due to energy loss. High turbulent kinetic energy is mainly concentrated near the working face and intake/return airways. The turbulent kinetic energy distribution and air-flow velocity vector diagram show that air-flow velocity decreases as the goaf deepens, with higher velocities at the upper and lower corners due to air leakage.

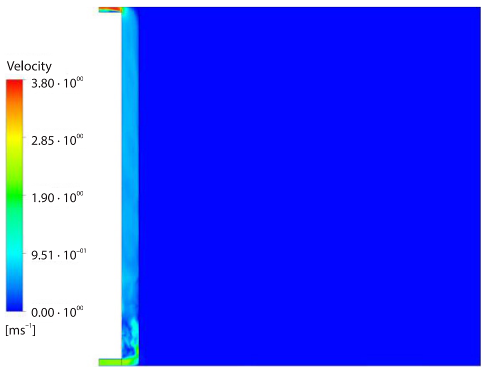

Figure 6. Air-flow velocity in the goaf

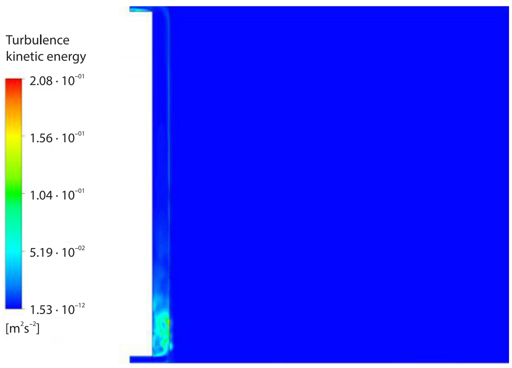

Figure 7. Turbulent kinetic energy distribution

Conclusion

This study used numerical simulation methods to systematically analyze the oxygen concentration distribution, air-flow field, and turbulent kinetic energy characteristics in the goaf of the 11223 working face in Xiaojihan Mine, quantitatively delineating the *three zones* of spontaneous combustion. The results indicate: the oxidation zone on the intake side ranges from 80-115 m (width of 35 m), the middle part of the goaf ranges from 45-80 m (width of 35 m), and the return side ranges from 15-30 m (width of 15 m), consistent with field measurements.

The oxygen concentration on the intake side is significantly higher than on the return side, and high air-flow velocities and turbulent kinetic energy are concentrated near the working face and intake/return airways, providing a scientific basis for optimizing fire prevention and control technologies such as nitrogen injection and air leakage sealing.

Nomenclature

c_p – solid specific heat capacity, [Jkg^{-1}K^{-1}]
c_s – volume concentration of species, [s]
D_s – diffusion coefficient of species, [s]
k_t – solid thermal conductivity, [Wm^{-1}]
p – pressure, [Pa]
S_u – species generation rate per unit volume, [–]
S_T – viscous dissipation term, [–]
S_{v_i} – source term ($i = x, y, z$), [–]
T – gas temperature, [K]
t – time, [s]
v_i – gas velocity vector ($i = x, y, z$), [ms^{-1}]

Greek symbols

μ – dynamic viscosity, [Pa·s]
ρ – gas density, [kgm^{-3}]

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