Multi-field coupling laws of mixed gas in goaf

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Abstract

Residual coal in goaf easily causes spontaneous combustion, and provides a long-term existence fire source, then easily leads to secondary gas explosion. This paper has a systematic study on the laws of gas flow and heat transfer in goaf pre-and post residual coal spontaneous combustion by numerical simulation. Multi-field coupling changed laws of gas-air mixed gas 3D seepage field, concentration field and temperature field pre-and post residual coal spontaneous combustion in goaf have been obtained by discreeting mathematical model equations. The numerical simulation results coincide well with site observation data.

\textbf{Keywords:} goaf, spontaneous combustion, multi-field coupling, temperature field ;

1. Introduction

Goaf related gas disasters and fire are major problems urgently needing to be solved in the development of China's mining. In particular, residual coal in goaf easily causes spontaneous combustion, and provides a long-term existence fire source, then easily detonates gas explosion, causes grave casualties and economic losses\textsuperscript{[1]}. Coal combustion is lead to explode by only fire source and fire pressure is power source to form explode condition\textsuperscript{[2]}. CO, the main product of coal spontaneous combustion in goaf greatly increases the gas-air mixture explosion concentration limits. And under fire pressure, CH\textsubscript{4}, CO and the fresh air well mix and heat exchange between combustion zone and non-ignition zone, easily lead to gas explosion accidents\textsuperscript{[3]}. According to the small size spontaneous experiments, L. M. Yuan and

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A. C. Smith numerical simulated spontaneous combustion in goaf, and got their temperature and oxygen concentration field distribution[4]. This paper has an in-depth study on coupling laws of seepage field, concentration field and temperature field pre-and post residual coal spontaneous combustion in goaf, and has great significance on goaf gas drainage, prevention of residual coal spontaneous combustion and secondary gas explosion.

2. Mathematical model

2.1. Continuity equation

\[ \frac{\partial (\rho \phi)}{\partial t} + \nabla (\rho \mathbf{V}) = q \rho \]  

(1)

2.2. Momentum equations

Momentum equations are the key equations to establish mathematical model. Momentum equations include non-porous region momentum equation and porous momentum equation. Taking the additional source term method in porous momentum equation, momentum equations united into a consistent form.

Non-porous region momentum equation:

\[ \frac{\partial}{\partial t} (\rho \mathbf{V}) + \nabla (\rho \mathbf{V} \mathbf{V}) = -\nabla P + \nabla (\overline{\mathbf{f}}) + \rho g \]  

(2)

Porous momentum equation:

\[ \frac{\partial}{\partial t} (\rho \mathbf{V}) + \nabla (\rho \mathbf{V} \mathbf{V}) = -\nabla P + \nabla (\overline{\mathbf{f}}) + \rho g - \frac{\varphi \mu}{K_p} \mathbf{V} - C_z \frac{1}{2} \rho |\mathbf{V}| \mathbf{V} \]  

(3)

Momentum source term includes two parts, one is the viscous loss term (Darcy term is known) and the other is the inertial loss term.

2.3. Species equation

\[ \frac{\partial (\rho c_s)}{\partial t} + \nabla \cdot (\rho \mathbf{V} c_s - D_s \nabla (\rho c_s)) = S_s \]  

(4)

2.4. State equation

\[ \frac{P}{\rho} = \frac{ZRT}{M} \]  

(5)

2.5. Energy equation

\[ (\rho c_m) \frac{\partial T}{\partial t} + (\rho c_p) \mathbf{V} \nabla T - \beta T (\frac{\partial p}{\partial t} + \nabla \nabla p) = \nabla (\lambda_m \nabla T) + \left( \frac{\mu}{k} \right) \nabla \mathbf{V} + \varphi q^* \]  

(6)

3. Physical model and boundary conditions

The 11824-1 face and goaf in 8th seam of Luling Coal Mine are selected as simulation prototype. The
coal mining method is top coal caving mining method with along strike longwall mining technology, and the coal top falls freely. Face produced rate is 81%. The U type arrangements and all negative pressure ventilation with airflow distribution of 20 m³/s are used. The physical model is shown in Figure 1. The intake and return airflow roadway are 4 m wide and 3.5 m high. The working face is 5 m wide, 3.5 m high, 630 m long in strike and 150 m in dip, with 12° dip angle. Fractured zone is set to 21.32 m high.

Fig. 1. Physical model of mining stope

The gas-air mixture in goaf is assumed as incompressible ideal gas mixture. Goaf is set to porous media type. The intake airflow roadway is set as velocity-inlet, and the return airflow roadway is set as pressure-inlet. Realizable $k$–$\varepsilon$ two equation model is selected as viscous model.

4. Gas chemical reaction model and heat source

Gas chemical reaction model is finite rate / eddy dissipation model. There is no generally accepted residual coal spontaneous combustion mechanism at present. In this paper, the 4-step reaction mechanism of residual coal spontaneous combustion is established, namely coal volatile and coke deposition reactions, coal volatile oxidation reaction, coke oxidation reaction and CO oxidation reaction. The 4-step reaction is shown in Equations (7~10). Double competitive reaction model is adopted to describe reactions. Both Arrhenius rate and blend rate are calculated, and the smaller of the two values is chosen.

\[
\text{Coal} \rightarrow \text{Coal}_{\text{vol}} + \text{C} \quad (7)
\]

\[
\text{Coal}_{\text{vol}} + a_1O_2 \rightarrow a_2\text{CO}_2 + a_3H_2O \quad (8)
\]

\[
(1+b)C + (b+0.5)O_2 \rightarrow CO + b\text{CO}_2 \quad (9)
\]

\[
2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2 \quad (10)
\]

Where $a_1$, $a_2$ and $a_3$ are determined response factor, depending on the different volatile reaction level.

According to Golf Three Zones Theory and the calculation of coal spontaneous combustion zone, the golf gas-air mixture flows through a heat source of spontaneous combustion in residual coal zone. Therefore, a cube of 5 m × 5 m × 1.68 m with body heart (45, -35, 0.84) is set as heat source of residual coal spontaneous combustion in inlet side of golf, see Fig.2.

Equations are dispersed in finite volume method with second order upwind scheme discretization, the unsteady flow field is calculated, and numerical solution algorithm is SIMPLE based on the pressure correction method.
5. Simulation results

5.1. Distribution of gas pressure

Fig. 3 (a) and (b) show the distribution of gas pressure pre-and post residual coal spontaneous combustion. It can be seen that the pressure of return flow near the up-corner of the face is the minimum in two cases. Compared Fig.3 (a) with (b), a relative negative pressure zone is formed in spontaneous ignition source. Thus, low temperature gas flows around the source to be heated or involved in high-temperature chemical reaction.
5.2. Velocity vector distribution

Fig. 4. Distribution of velocity vector on \( z = 0.84 \) m plane (a) without spontaneous ignition source case; (b) with spontaneous ignition source case

It can be seen from Fig. 4, gas seepage field is affected by high temperature of residual coal spontaneous combustion. Gas changes direction and flows to spontaneous high-temperature zone. High temperature range of the flow field is growing and gas flow velocity has accelerating trend under the action of high temperature of residual coal spontaneous combustion.

5.3. Temperature distribution

Fig. 5. Gas temperature distribution at a given time after spontaneous combustion (a) 3D distribution; (b) on \( x = 45 \) m plane; (c) on \( y = -35 \) m plane; (d) on \( z = 0.84 \) m plane

It can be seen from Fig. 5, affected by the high temperature zone, gas temperatures around the zone
gradually increase. The raising temperature range gradually expands too, and the range expands mainly along the shallow goaf. The high-temperature gas range has the trend of expansion from inlet side to return air side.

As shown in Fig. 5, along the strike, gas temperatures have a greater increase in inlet side. From the down-corner angle to 90 m away from the working face, the temperatures rises to 330 ~ 340 K. Accordingly, golf measured temperatures was 341 K and 346 K in 38.3 m and 63.3 m away from the working face in on-site observations[1]. The simulation results are coincides well with that from on-site observations. Therefore, there is a residual coal spontaneous combustion zone in the inlet side in goaf prototype.

5.4. CH₄ concentration distribution

Fig.6 shows the distribution of CH₄ mass fraction pre-and post spontaneous combustion.

As can be seen in Fig.6, The CH₄ concentration of whole goaf has slight reduce after spontaneous combustion. But CH₄ concentration in and around spontaneous combustion source do not reduce, on the contrary, has slightly increase. This is due to temperature of spontaneous combustion source is relatively lower in the numerical example, and do not reach the ignition point of CH₄. And CH₄ is not lit. Fire pressure is formed in high temperature of spontaneous zone, accordingly CH₄ outside the zone flow to the
zone.

6. Conclusions

Coupling laws of 3D mixed gas seepage field, concentration field and temperature field in goaf pre-and post residual coal spontaneous combustion are studied by numerical simulation. Finite rate/eddy dissipation model and 4-step reaction mechanism of residual coal spontaneous combustion are established. The results show that gas pressure field is affected by high temperature of residual coal spontaneous combustion and there is a gas negative pressure zone in residual coal spontaneous combustion high-temperature zone. The low-temperature gas around the high-temperature zone has been heated or involved in the spontaneous chemical reactions. Gas seepage field is also affected by residual coal spontaneous combustion high temperature field. The original gas flow direction close to the high temperature zone has been changed and gas flow velocity has been accelerated. The gas temperature field is affected by gas seepage field in return. High temperature gas zone expand mainly in shallow part of goaf and high temperature gases flow from inlet side to return side. After spontaneous combustion, \( \text{CH}_4 \) concentration decreases in the whole goaf, whereas increases slightly in the spontaneous combustion zone. The numerical simulation results coincide well with site observation data.

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