Effect of inert gas injection on gas explosion in the process of sealing fire zone

ZHANG Li-li, LI Cheng-yu*

Xinjiang Institute of Engineering, Urumqi 830091, Xinjiang, China

15099605118@126.com

Abstract. In order to study the influence of inert gas injection to gas explosion in the process of fire zone sealing, tunnel fire model was established by COMSOL software, and numerical simulation is carried out to study change laws of flow field and concentration field in the process of fire zone sealing. Through comparing the distribution law of flow field and concentration field whether the inert gas injection and different flows, obtained the influence of inert gas injection to gas explosion in the process of fire zone sealing. As the decrease of entrance average wind speed, the maximum wind speed in the centre vertical section of tunnel gradually reduces. when the entrance average wind speed is 1m/s, counter current layer is produced near the fire resource, length and thickness of counter current layer and maximum current speed rises with the declining of the entrance average wind speed, and swirl will be formed when the entrance average wind speed is less than 0.01m/s. In the process of fire zone sealing, the maximum gas concentration in the fire area and on the side of leeward goes up with the declining of entrance average wind speed.

1. Introduction
When the mine fire to a certain extent can’t be directly extinguished, the fire zone must be closed. However, it is very easy to cause gas explosion in the process of fire zone sealing. How to close the fire zone quickly, safely and efficiently is the difficult point of fire area management [1]. In order to ensure the safe and efficient closure of the fire zone, it is necessary to study the law of gas migration and the explosion hazard in the process of fire zone sealing. In recent years, some scholars have studied the law of heat and mass transfer, gas accumulation and danger during the process of fire zone sealing, and the law of spontaneous combustion induced gas explosion in the process of fire zone sealing [1-8]. In this paper, combined with the existing research results, using numerical simulation method, to study the influence of inert gas injection to gas explosion in the process of fire zone sealing. Because numerical simulation of fire zone involves the coupling of multiple physical fields, this paper uses COMSOL Multiphysics software for numerical simulation.

2. To establish models and conditions
The calculating model is a horizontal rectangular tunnel designed with 4 m width, 3 m high and 50 m long. The roof, floor and sides of tunnel are designed as 0.5m thick rock. Fire source is coal heap, the center of coal heap is 16m from the entrance, the coal heap with basal diameter of 1m, height of 1m and top face diameter of 0.5m is shown in Fig.1. The model shown in Fig.2 uses free tetrahedron mesh, coal heap surface shown in Fig.3 is encrypted separately with free triangle, the whole model is divided into 434533 meshes.
There are three physical fields of flow field, heat transfer field and mass transfer field in fire zone. Flow field uses turbulence model, as inflow is in the left and outflow is in the right, forced convection exists because of volume force effect on airflow after being heated, entrance initial normal speed is 2m/s, outlet is pressure boundary. The model uses solid-gas coupling heat transfer model, sets coal heap as heat source, and supposes that there are enough combustibles in the whole combustion process, this paper estimates heat output with oxygen consumption method because of different coal quality with different generating heat, the energy generated by oxygen consumption per unit mass is 13.1MJ/kg, coal heap, roof and floor, and sides are solid heat transfer, because external is formation rock, the external boundary is set as convection cooling, airflow is fluid heat transfer, initial temperature is 293.15K(20℃); Mass transfer uses convection diffusion model, each gas concentration in airflow entrance is constant, the combustion reaction of coal occurred in coal heap surface, methane emits from tunnel wall. The initial value of the entrance: O₂ concentration is 21%, CH₄ concentration is 0.1%, CO₂ concentration is 0.03%, CO concentration is zero. At the initial stage of fire is oxygen-enriched combustion. Oxygen concentration is more than 15%, the oxygen consumption of combustion reaction on the coal heap surface has been calculated by that. The gases produced mainly consist of CH₄, CO and CO₂, the ratio of gases produced is 0.05:1:1 when fire zone temperature is before 1300℃, the ratio of gases produced changes to 0.05:1:2 after fire zone temperature reaches 1300℃, gas emission of tunnel wall is 0.048 m³/s.

Fig.1 Calculation model

Fig.2 Mesh generation

Fig.3 Local grid refinement
As entrance wind speed gradually decreases in the process of sealing fire zone, flow field is inevitably in change. The effects of reducing air supply volume on heat and gases produced in combustion are ignored, supposing that air supply volume decreases linearly, closure process continues for 60 minutes, a little air leakage exits in fire zone (0.12m$^3$/s), entrance wind speed boundary is changed to piecewise function about time.

\[
\begin{cases}
\nu = 0.01 & t > 3582 \\
\nu = 2 \times \frac{3600 - t}{3600} & t \leq 3582
\end{cases}
\]

The entrance of the left side is the closed construction site, and a 20cm diameter injection inert gas pipeline outlet is arranged at the upper side of the seal-wall, and the inert gas is injected, the inert gas flow is 300m$^3$/h, and the air leakage is 0.12m$^3$/S, the other boundary conditions remain unchanged.

3. Simulation of injection inert gas flow field in closed
The maximum wind speed change trend of centre vertical section of tunnel in the process of fire zone sealing is shown in Figure 4. The thickness change trend of counter current layer is shown in Figure 5, and the length change trend of counter current layer is shown in Figure 6. The maximum counter current speed change trend is shown in Fig.7. The flow field change of centre vertical section during the sealing process is shown in Fig. 8 ~ Fig.12.
It can be seen from Fig.4 ~ Fig.7 and Fig.8 ~ Fig. 12 that the maximum wind speed at the centre vertical section of the tunnel decreases with the decrease of the entrance average wind speed in the process of fire zone sealing. According to the arrows of streamline and velocity vector, when the average entrance wind speed is 1m / s, the counter current layer is formed near the fire source. The length and thickness of the counter current layer, the maximum counter flow speed all increase with the decrease of the entrance average wind speed. As the sealing process progresses, the entrance wind speed decreases gradually, and when it reaches 0.01m / s, eddy current is formed at the entrance.

When the closure is completed, the maximum wind speed of centre vertical section of tunnel is 4.72m / s, the counter current layer thickness is 1.4m, the counter current length is 9.3m and the maximum counter current speed is 4.1m / s. The maximum wind speed, counter current length, counter current layer thickness and counter current speed of the central vertical section of the tunnel are smaller than those of the non-injected inert gas.

4. Simulation of Gas Concentration Variation during Closed with Injection of Inert Gas
The trend of the maximum gas concentration in the vertical section of the centre of the tunnel is shown in Figure 13, and the trend of the maximum gas concentration on the downwind side of the fire source is shown in Figure 14, the gas concentration distribution of the centre vertical section of tunnel is shown in Figure 15 to Figure 19. The Nitrogen concentration distribution of the centre vertical section of tunnel is shown in Figs. 20 to 24.
Fig 13: The maximum CH$_4$ concentration of centre vertical section of tunnel

Fig 14: The maximum CH$_4$ concentration below fire source

Fig 15: Distribution map of CH$_4$ concentration as entrance average wind speed is 1.5 m/s

Fig 16: Distribution map of CH$_4$ concentration as entrance average wind speed is 1 m/s

Fig 17: Distribution map of CH$_4$ concentration as entrance average wind speed is 0.5 m/s

Fig 18: Distribution map of CH$_4$ concentration as entrance average wind speed is 0.25 m/s

Fig 19: Distribution map of CH$_4$ concentration as entrance average wind speed is 0.01 m/s
It can be seen from Figure 15 to Figure 19 that the maximum gas concentration in the fire zone gradually increased to a maximum of 2.11%, and the maximum gas concentration at the downwind side increases slowly with the decrease of the entrance average wind speed, the maximum gas concentration at the vertical section of the middle of the tunnel appears at the edge of the counter current layer. When the wind speed is reduced to 0.25 m/s, the maximum gas concentration at the vertical section of the tunnel is 1.92%, present to 36 m ahead of the fire source near the roof, the maximum gas concentration in the vertical section of the tunnel is 2.11%, after the seal-wall, the gas concentration at the edge of the counter current layer is 1.48%. It can be seen that when the wind speed is less than 0.25 m/s, the injected gas flow rate is relatively small, the flow rate is relatively small, inert gas mixed with the gas in front of the fire slowly, formation squeeze on fire area, due to interaction with the counter current layer, the lighter gas moves and converges toward the entrance side near the top plate.

Try to change the parameters of inert gas injection, inert gas flow change to 1000 m$^3$/h, wind speed change to 0.25 m/s and 0.01 m/s, gas concentration distribution is shown in Figure 20, Figure 21.

The maximum concentration of gas is 1.36%, 1.63%, the average gas concentration of the whole fire zone is less than 1%, and the dangerous of gas emission eliminated. So field application should increase injection inert gas flow rate and injection inert gas speed as far as possible.

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From Fig.22 to Fig.26, it can be seen that with the decrease of the wind speed in the fire zone, the nitrogen concentration in the fire zone increases gradually, and the injected nitrogen gas before the fire source is not mixed uniformly with the air in the fire area. Affected by thermodynamic nitrogen gas well blended with air in the fire area near the fire source.

5. Summary
(1) In the process of fire zone sealing, when inert gas flow is 300m$^3$/h, the maximum wind speed at the central section of the tunnel decreases with the decrease of the entrance average wind speed. When the entrance average wind speed is less than 1 m/s, the counter current layer is formed in the vicinity of the fire source. The thickness and length of the counter current, the maximum counter flow speed all increase with the decrease of the entrance average wind speed.
(2) When inert gas flow is 300m$^3$/h, and the wind speed of the fire zone reduce to 0.01m/s, swirl will be formed at the entrance, the maximum wind speed of centre vertical section of tunnel is 4.72m/s, the counter current layer thickness is 1.4m, the counter current length is 9.3m and the maximum counter current speed is 4.1m/s. The maximum wind speed, counter current length, counter current layer thickness and counter current speed of the central vertical section of the tunnel are smaller than those of the non-injected inert gas.
(3) When inert gas flow is 300m$^3$/h, the maximum gas concentration in the fire zone gradually increased to a maximum of 2.11% in the process of fire zone sealing, when the wind speed is less than 0.25m/s, the injected gas flow rate is relatively small, the flow rate is relatively small, inert gas mixed with the gas in front of the fire slowly, formation squeeze on fire area, due to interaction with the counter current layer. The lighter gas moves and converges toward the entrance side near the top plate, the maximum gas concentration at the vertical section of the tunnel is 1.92%, present to 36m ahead of the fire source near the roof.
(4) When inert gas flow change to 1000 m$^3$/h, nitrogen gas well blended with air in the fire area near the fire source. the average gas concentration of the whole fire zone is less than 1%, and the dangerous of gas emission eliminated. So field application should increase injection inert gas flow rate and injection inert gas speed as far as possible.

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