Simulation on oxygen concentration and temperature under condition of liquid N₂ injection into mine goaf

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Abstract

To prevent coal spontaneous combustion in mines, liquid N₂ was injected into goaf to dilute oxygen concentration and decrease temperature. In this study, the goaf was modeled as a 3-D porous medium based on stress distribution. The variation of O₂ and temperature distributions influenced by liquid N₂ injection was simulated based on the multi-component gases transport and the Navier-Stokes equations using Fluent. Simulation results show that high temperature area is 15m after workface on the air-return side and air-intake side in goaf without liquid N₂ injection; liquid N₂ injection changes the temperature distribution of the goaf. At the beginning, the area where temperature influenced by liquid N₂ was small, and then the area influenced by low temperature N₂ becomes larger gradually. Temperature distribution at time of 90min is very similar with steady-state solution, that is to say the temperature distribution becomes stable 1.5 hours after. Meanwhile, when the N₂ injection entrance was located at 15m after workface on the air-return side, the volume of region with temperature \( \leq 300 \, \text{K} \) is the smallest, which means the cooling
effect is the worst.

Keywords: Goaf, Numerical simulation, Liquid N₂, Oxygen distribution, temperature distribution.

Keywords

Nomenclature

\[ A \] Pro-factor

\[ a_0 \] Attenuation rate in the tendency direction

\[ a_1 \] Attenuation rate in the strike direction

\[ b_0, b_1 \] Adjusting parameters

\[ C \] Mass concentration

\[ c_p \] Specific heat capacity, J/(Kg.°C).

\[ D \] Diffusivity (m²s⁻¹)

\[ E \] Activation energy (kJ/mol)

\[ \mathbf{\hat{g}} \] Vector of gravity (ms⁻²)

\[ H \] Height (m)

\[ K \] Coefficient of rock dilatation

\[ k_p \] Heat transfer coefficient

\[ K_{p,max} \] Initial caving coefficient

\[ K_{p,min} \] Coefficient of bulk increase

\[ k \] Permeability (m²)

\[ k_0 \] Base permeability (m²)
$L$ Length (m)

$\dot{m}$ Mass generation rate (kg/m$^3$/s)

$P$ Pressure (N/m$^2$)

$R$ Ideal gas constant, $8.314$ J/(mol·K)

$S$ Source term

$S_T$ Thermal source

$T$ Temperature (K)

$t$ Time (s)

$u$ Velocity vector

$u, v, w$ Velocity components (m/s)

$W$ Width (m)

$x, y, z$ Spatial coordinates

**Greek symbols**

$\alpha$ Reaction constant

$\varepsilon$ Adjusting parameter

$\xi$ Porosity

$\mu$ Dynamic viscosity (kg/(m·s))

$\rho$ Density of the gas mixture (kg/m$^3$)

**Subscripts**

$i$ Gas component $i$
1. Introduction

Spontaneous combustion of coal is an issue that threatens the development of the coal industry worldwide[1]. Among China’s state-owned collieries, 56% of the mines have been jeopardized by spontaneous combustion, and the combustion incidents in these mines account for 90 – 94% of all coal mine fires [2]. In US, Indian and Australian coal mines, most fires also occur due to spontaneous combustion[3]. There are two common ways to prevent coal spontaneous combustion. One is decreasing oxygen concentration; if the oxygen were not enough, coal oxidation which is the initial stage of coal spontaneous combustion would not happen easily. Another way is to decrease the goaf temperature and maintain it always below coal ignition point[4,5].

In order to decrease oxygen concentration and temperature in goaf, liquid nitrogen would usually be injected into goaf[6,7]. However, little is known of critical parameters such as the optimal and economical positions and time in injecting liquid N$_2$ gas. The influence scope with injection of liquid N$_2$ in goaf is quantitatively undetermined. Meanwhile, little is known about the difference of the effects on the O$_2$ concentration, temperature distribution during injection of liquid N$_2$. As a matter of fact, improper position of injection may increase the likelihood of mine fires.

In this paper, we developed a 3-D CFD model to study gases transport and temperature distribution with injection of liquid N$_2$ gas into mine goaf. In this model, the coupling between chemical reactions in the coal seam and O$_2$ gas transport through
adjacent rocks was taken into account. The distributions of O₂, N₂ gases and temperature in the goaf were obtained. We also discussed the inverting effect due to the location of perfusion pipeline’s exports. The results were used to evaluate the hazard of coal spontaneous combustion in specific areas of the goaf under condition of liquid N₂ injection. The research would be useful for prevention of coal spontaneous combustion.

2. Mathematical Models

In a mine goaf, coal desorbs methane and self-ignition of coal consumes O₂, leading to variance of gases concentration in the field. The species mass conservation equation under incompressible flow condition is:

\[
\frac{\partial}{\partial t} \xi \rho C_i + \rho \nabla \cdot (C_i \mathbf{u}) = \xi \rho \nabla \cdot \left( D_i \nabla (C_i) \right) + S_i \quad i = 1, 2, 3, 4 \quad (1)
\]

Where \( \rho \) is the density of the gas mixture, \( C_i \) and \( D_i \) are the mass concentration and diffusion coefficient of the gas species, \( \xi \) is porosity, \( S_i \) is the source term, \( t \) represents time, \( \mathbf{u} \) is velocity vector. Subscripts 1 to 4 represent N₂, CO₂, O₂ and CH₄ gas in order. In the present study, \( S_1 = S_2 = 0 \) everywhere, \( S_3 = S_4 = 0 \) in the laneway, and in the goaf \( S_3 \) and \( S_4 \) are described by[8]

\[
S_3 = -AC_3^\alpha e^{\frac{E}{RT}} \quad (2)
\]

\[
S_4 = \dot{m}_4 \quad (3)
\]

Where \( A \) is the pro-factor, decided by the species of coal and the test methods; \( \alpha \) is a constant, varying from 0.5 to 1.0; \( E \) is the activation energy, varying between 12-95 kJ/mol depending on coal species; \( R \) is the ideal gas constant; \( T \) is the absolute
temperature; and $\dot{m}_4$ is the CH$_4$ gas mass generation rate per unit volume measured by field experiment.

The energy conservation equation in goaf:

$$\rho \frac{\partial T}{\partial t} + \rho \nabla \cdot (T \mathbf{u}) = \frac{k_f}{c_p} \nabla \cdot (\nabla T) + S_T$$

(4)

where, $c_p$ means specific heat capacity, J/(kg·℃), $T$ is the temperature, $k_f$ is the heat transfer coefficient, $S_T$ is thermal source, which contains the energy releases in the self-ignition phase of coal, consisting of the thermal energy converted from the thermal energy and chemical reaction. $S_T$ is described by,

$$S_T = - q \cdot S_3$$

(5)

where $q$ is thermo release when coal consume one mole oxygen.

We assume that the mine goaf is an isotropic porous medium. Since the gas mixture could be assumed as Newtonian fluid, the momentum conservation equations in the porous goaf are\textsuperscript{[9,10]}

$$\frac{\rho}{\xi} \left( \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = - \nabla \cdot \mathbf{P} + \frac{\mu}{\xi} \cdot (\nabla^2 \mathbf{u}) + \rho \mathbf{g} - \frac{\mu}{k} \mathbf{u}$$

(6)

where $P$ is the pressure, $\mu$ is the dynamic viscosity of the gas mixture, $\mathbf{g}$ is the vector of gravity, $k$ is the permeability of the goaf.

The pressure gradient and concentration gradient drive the gases seep into the goaf. When the gas transfers in goaf, it is hindered with the viscous resistance and inertia resistance. All these factors are highly associated with the permeability distribution of the goaf. Qian and Li\textsuperscript{[11]} illustrated a function between the goaf permeability and the surrounding rock stress, which is an exponential distribution at the strike direction.
According to the Carman-Kozeny equation, permeability can be described as:

\[
k = \frac{k_0}{0.241} \cdot \left(1 - \xi \right)^2 \quad (7)
\]

where \(k_0\) is the base permeability of the broken rock at the maximum porosity and it was taken as \(1 \times 10^{-3}\) m², which places it in the “open jointed rock” range according to Hoek and Bray [12].

Porosity model and introduced a 3-D porosity model as [14]

\[
\xi = \left[1 - \left(K_{p,\text{min}} + (K_{p,\text{max}} - K_{p,\text{min}}) \times \exp\left[\frac{-a_1 \times (y + b_1) \times \left(1 - e^{-c_1(x+b_2)}\right)}{h}\right]\right]\right] \times \left(1 - \frac{z}{h}\right) \quad (8)
\]

where \(K_{p,\text{max}}\) is the initial caving coefficient of bulk increase and its value is 1.6, \(K_{p,\text{min}}\) is the coefficient of bulk increase in compaction and its value is 1.1, \(a_0\) and \(a_1\) are the attenuation rate in the tendency and strike direction, respectively, and their values are 0.0368 and 0.268, \(c_1\) is the adjusting parameter and its value is 0.233, \(b_0\) and \(b_1\) are the adjusting parameters in the strike direction and at the tendency, and their values are 0.8 and 15. \(H\) is the height of goaf. The porosity distribution for the goaf in the present study is shown in Fig. 3.

The boundaries for the simulation model were established based on the field experimental conditions and described below. Compared with goaf, the porosity and permeability of coal seam around the goaf are very small, so it could be assumed as solid wall. Thus, at all boundaries of the goaf and the laneway we have:

\[
\mathbf{u} = 0, \quad C_i = 0, \quad T = 300\text{K} \quad (9)
\]

At the fresh air inlet of the laneway:
\[ u = v_{\text{air}} \quad C_1 = 0.77 \]
\[ v = w = 0 \quad C_2 = C_4 = 0 \]
\[ \quad T = 300K \] (10)

At the air outlet of the laneway:
\[ P = p_0, T = 300K \] (11)

In the case with N\textsubscript{2} injection, the injection inlet:
\[ u = v_{N_2} \quad C_1 = 1 \]
\[ v = w = 0 \quad C_2 = C_3 = C_4 = 0 \]
\[ \quad T = 156.8K \] (12)

In Which, \( v_{\text{air}} \) is the air velocity calculated by the airflow rate and cross section size of laneway. \( v_{N_2} \) and \( v_{CO_2} \) are the velocities of inert \( N_2 \) and \( CO_2 \) injection, respectively, calculated by injection rate and cross section size of the injection port. \( p_0 \) is the pressure around the mine goaf. The return airway is set as a free outflow condition.

3. Workface model

Fig.1 shows the goaf model employed in the simulation, adapted from the conditions in field measurement described above. The model goaf is 180m long, 100m wide, and 40m high. The coal seam angle and strike angle are 0°. The cross section size of both the workface and laneway is 3m × 3m. The length of the laneway is 30m. The coordinate origin is located at the junction of the workface and the goaf on
the intake-side. Inert gas injection was considered from one of the six injection ports from either the air intake or return side, distance from workface is 15, 25, 35m respectively.

The simulation model is built based on a complex mechanical coal mining workface with fully mechanized top coal caving technology. The thickness of the coal seam is between 4.3~12.2m, with an average thickness of 10.35m. Since it is a fully mechanized top coal caving, there was some coal would be leaving in the goaf, we assumed that 30% of coal was left in goaf under this fully mechanized top coal caving technology, the thickness of coal in goaf was about 3m, shown by Figure 2. The air quantity of mining workface is 768m³/min, O₂molar concentration in the fresh airflow is 20.95% (equals to mass concentration at 23%), and the ventilation system of workface is a “U” type model. Quantity of lower N₂ is 600m³/h, temperature of N₂ when it is injected into goaf is 156.8K.

3.1 Process of liquid N₂ injection

N₂ is usually injected into goaf from the air intake laneway or air return laneway using a steel pipe with diameter of 108m. In this simulation, liquid N₂ gasified in air intake or air return laneway, and then low temperature N₂ was injected into goaf from steel pipe (length of pipe is about 50m). Since N₂ gasification temperature is about 80K(-193 °C), after 50m pipe flowing the temperature would increase to 156.8K around, temperature of N₂ when it is injected into goaf is 156.8K.

3.2 Simulation model and meshing

The simulation model was meshed using unstructured grids. Several mesh sizes
were considered. We found that a grid system containing 543,874 elements could give satisfactory convergent results and this grid size was adopted for simulations thereafter.

FLUENT (ANSYS 14.5) was used to solve the governing equations in the present simulations. The species transport model is actually a built-in model in FLUENT[13]. Meanwhile, the secondary development of FLUENT was carried out with User Defined Function (UDF). The porosity profile and inertia resistance were defined with “DEFINE_PROFIL”. The oxygen consumption rate was defined with “DEFINE_SOURCE”. Then the UDF was combined with FLUENT. The convergence of all the variables was that their residuals are less than $10^{-3}$.

4. Results and Discussion

4.1 Temperature and oxygen distributions without N2 injection

![Figure 3: Oxygen distribution in goaf without N2 injection](image)

Figure 3: Oxygen distribution in goaf without N2 injection
From Fig. 3, it is seen that the O₂ gas concentration decreases as distance (x value) increases. Since the air leakage flows into the goaf under the mine ventilation pressure, the farther the location is away from the workface, the weaker the air leakage flow is. Meanwhile, the residual coal desorbs methane and coal oxidation consumes oxygen; all these factors decrease O₂ concentration with increasing x distance. It is observed that O₂ concentration is a little bit higher on air-intake side and air-return side than the middle parts.

Fig. 4 shows that the temperature first increases and then decreases as distance (x value) from workface increases. The high temperature area in goaf is 15m behind workface, high point of temperature is on the air-return side and air-intake side. The reason is that temperature increased is determined by heat release from coal oxidation and heat dissipation caused by air leaking flow. In the workface, since the air flow is strong, though coal oxidation is quickly, the heat dissipation caused by air flow is also strong, and the temperature is not so high. With the increasing of distance from workface, air leaking flow turns weak, heat dissipation would be small, so
temperature will be a little higher. At the area far from workface, because of the distance is so long from workface that the leaking air flow is so weak and could not provide sufficient oxygen for coal oxidation, there is no heat releasing and temperature will turn down. From Fig.4 we can find that temperature on both air-return and air-intake sides is little higher than it is in the middle part. The reason is that porosity is larger on air-return and air-intake sides. Air leaking is strong so oxygen concentration is higher, and speed of coal oxidation is high, heat release would be strong here.

4.2 Evolution of temperature and oxygen distributions with liquid N2 injection
Figure 5 Time development of temperature distribution at the goaf floor level with liquid N₂ injection

Figs.5 (a-d) shows the time development of temperature distribution at the ground level with continuous liquid N₂ injection. It is found that liquid N₂ injection changes the temperature distribution of the goaf. At the beginning, the area where temperature influenced by liquid N₂ was small, and then the area influenced by low temperature N₂ enlarges gradually. Temperature distribution when time is 90min is very similar with the steady-state solution, that is to say the temperature distribution becomes stable 1.5 hours after.

(c) 90min

(d) Steady
Figure 6 is the corresponding time development of oxygen molar concentration distribution at the ground level with continuous liquid $N_2$ injection. From the picture we can find that $N_2$ injection changes oxygen distribution of the goaf. From Fig.6, it is seen that the location around the $N_2$ injection entrance has an $O_2$ concentration $<5\%$. It indicates that $N_2$ gas flows up in the goaf. Since the density of $N_2$ is less than that of
the air, the buoyancy has a major influence on the \( \text{N}_2 \) gas distribution. It is found that \( \text{N}_2 \) injection changes the oxygen distribution of the goaf. It dilutes the oxygen and reduces the oxygen concentration. \( \text{O}_2 \) concentration in the zone near the inert gas injection position decreases sharply in the first 10 min, and then the area influenced by inert gas enlargens gradually. The \( \text{O}_2 \) distribution becomes stable 90 min after injection.

4.3 Cooling effects when liquid \( \text{N}_2 \) was injected from different entrances

(a) 15 m after workface at air-return side (steady)

(b) 25 m after workface at air-return side (steady)
(c) 35m after workface at air-return side (steady)

(d) 15m after workface at air-intake side (steady)

(e) 25m after workface at air-intake side (steady)
Figure 7. Steady state temperature distribution when liquid N\textsubscript{2} was injected from different entrances

Fig. 7 shows the cloudy pictures of temperature distribution when liquid N\textsubscript{2} was injected from different entrances. From the contrasts of these pictures we can see that no matter where the injection is, liquid N\textsubscript{2} injection can decrease temperature around the entrance. The temperature distribution is not the same for different injection entrance. N\textsubscript{2} injection would reduce temperature as well as the area of the spontaneous combustion dangerous zone.
From the simulation result we can also find out that temperature in workface would not be influenced by liquid N$_2$ injection no matter where the injection entrance is. When liquid N$_2$ was used for coal spontaneous combustion prevention and controlling, the goaf temperature distribution influenced by N$_2$ injection should also be considered as well as oxygen concentration distribution. In order to discuss the cooling effect by liquid N$_2$ injection, volume of region where temperature <300k in coal area (since coal was in the bottom with height of 3m, so we just discuss the volume of region where temperature is lower under 300K at coal area.) in goaf was extracted from the simulation result. Fig. 8 is the volume of region where temperature <300k at goaf coal area when liquid N$_2$ injection from different ports with time development. From the picture we can find that no matter where is the location of injection entrance, with the time development the volume of where temperature is below 300K turns larger at first, and then gets to stable status gradually. When the N$_2$ injection entrance was located at 15m after workface on air-return side, the volume of region temperature <300k is the smallest which means the cooling effect is the worst. Meanwhile, when the injection entrance was located at 15m after workface on the air-intake side, the volume of region temperature <300k is the biggest. In this condition the cooling effect is the best.

5. Conclusions

Simulations of gases and temperature distributions in goaf based on the 3-D model were carried out. The following main conclusions were drafted:
(1) High temperature area is 15m after workface on the air-return side and 
air-intake side in goaf without N$_2$ injection.

(2) Liquid N$_2$ injection changes the temperature distribution of the goaf. At the 
beginning, the area where temperature influenced by liquid N$_2$ was small, and then the 
area influenced by low temperature N$_2$ enlargens gradually. Temperature distribution 
when time is 90min is very similar with steady state solution. That is to say the 
temperature distribution becomes stable 1.5 hours after.

(3) From the simulation result we also find out that the temperature in workface 
wouldn’t be influenced by liquid N$_2$ injection no matter where the injection entrance 
is.

(4) When the injection entrance was located at 15m after workface on the air-intake 
side, the cooling effect of liquid N$_2$ injection is the best. Meanwhile, when the N$_2$ 
injection entrance was located at 15m after workface on the air-return side, the 
volume of region temperature < 300k is the smallest which means the cooling effect is 
the worst.

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