Prediction method of coal mine goaf temperature and its practical application

Zhang Xinhai\textsuperscript{1,2}, Zhu Hui\textsuperscript{1*}

\textsuperscript{1} College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China
\textsuperscript{2} Key Laboratory of Western Mine Exploitation and Hazard Prevention Ministry of Education, Xi'an 710054, China
\textsuperscript{*}Corresponding author’s e-mail: zhangxinh71@126.com

Abstract. Spontaneous combustion of coal seams in goaf seriously threatens the development of the coal mining industry. The prediction of goaf temperature is of great significance for mine disaster prevention. Based on the energy conservation equation of floating coal in goaf, the analytical solution of the steady-state temperature field in goaf is derived in this paper, and the temperature of goaf can be calculated simply through a series of physical and chemical parameters. This method is applied to Kaida Coal Mine to calculate the temperature of goaf at the return air side of 46205 working face. The results show that although there is some error between the calculated value and the measured value of the temperature in goaf, the predicted results can reflect the change rule of the temperature in goaf, and provide some guidance for the prevention and control of coal spontaneous combustion in goaf. With the increase of buried depth, the floating coal temperature rises first and then decreases. It is estimated that the maximum temperature of goaf is 27.11\degree C, which is located 25m deep in goaf.

1. Introduction
Spontaneous combustion of coal seam will not only cause the loss of coal resources, but also cause harm to people's life safety\textsuperscript{1,2}. According to incomplete statistics, the total number of deaths caused by mine accidents in China from 2007 to 2016 is 4,935, among which the number of deaths caused by fire accounted for about 7.32 percent\textsuperscript{3}. Moreover, it should be noted that spontaneous combustion of coal can also induce other disasters such as gas and dust explosions in coal mines\textsuperscript{4}. More than 90\% of coal seams in China are inflammable coal seams, and coal spontaneous combustion in goaf accounts for more than 60\% of internal coal fires\textsuperscript{5}. Therefore, it is of great significance for mine disaster prevention and control to predict the possible high-temperature area in goaf.

There are many factors affecting the temperature of floating coal in goaf\textsuperscript{6,7}, and many parameters in goaf are difficult to be measured\textsuperscript{8}. Therefore, the spontaneous combustion of floating coal has always brought great challenges to coal mining. Since the 1980s, many researchers such as Schmal, D.\textsuperscript{9}, Sasaki, K.\textsuperscript{10}, Brooks, K.\textsuperscript{11}, and McNabb, A.\textsuperscript{12} have conducted a large number of studies on spontaneous combustion of floating coal in goaf, making contributions to the prevention and control of spontaneous combustion of coal. But these studies did not establish a model to predict the temperature of goaf. At the beginning of this century, according to the environmental conditions of goaf, Jingceai, X.\textsuperscript{13} established a dynamic mathematical model of temperature distribution and time of goaf, which can predict the spontaneous combustion risk of goaf at different propulsion speeds, but it is
inconvenient to be applied in practice due to the complexity of calculation. In recent years, due to the development of computer science, many scholars [14,15] have used COMSOL, CFD, and other computing softwares to numerically solve the temperature of mine goaf. However, due to the large amount of computation, these methods are also mainly used in theoretical research. Therefore, it is necessary to explore a simple and practical model to evaluate the floating coal temperature in goaf.

Based on the self-heating physical model of floating coal, the analytical solution of goaf temperature related to environmental parameters, oxidizing heat release strength of floating coal, oxygen consumption rate, and other parameters is obtained. Therefore, the temperature of floating coal in goaf can be predicted and evaluated, which provides guidance for mine fire prevention and control.

2. Prediction equation of coal body temperature in goaf

2.1. Energy conservation equation of heat generation and heat dissipation process of floating coal

The floating coal in goaf generates heat mainly through oxidative exothermic reaction with oxygen, and the heat is mainly dissipated through heat exchange with roof, floor, and wind flow [16]. According to the principle of energy conservation, when the heat storage of floating coal in goaf remains unchanged, the temperature of floating coal is stable. In this case, the heat generation and heat dissipation of floating coal have the following relations:

\[
\text{div}[\lambda \, \text{grad}(T_m)] + q(T_m) - \text{div}(n \rho_s \, c_e \, \dot{U} \, T_m) = 0
\]

Where, \( \lambda \) is the thermal conductivity of loose coal, (J·s\(^{-1}\)·cm\(^{-1}\)); \( T_m \) is coal body temperature, °C; \( q(T_m) \) is the oxidation-exothermic strength of residual coal in goaf, (J·cm\(^{-3}\)·s\(^{-1}\)); \( \rho_s \) is the airflow density on the working face, (g·cm\(^{-3}\)); \( c_e \) is the Heat capacity of airflow, (J·g\(^{-1}\)·°C\(^{-1}\)); \( Q \) is the air leakage intensity in goaf, (cm\(^3\)·s\(^{-1}\)·cm\(^{-2}\)).

2.2. Analytical solution of the energy conservation equation

Assuming that the float coal thickness in goaf is consistent, the float coal temperature \( T_m \) is a function of position \( (x, z) \):

\[
T_m = X(x) \cdot Z(z)
\]

Where \( x \) is the distance between the inside of the goaf and the working face; \( z \) is the distance from the center of the coal seam (\( z=0 \) is the center of the floating coal seam).

Substitute Formula (2) into formula (1), and the following equation can be obtained:

\[
\lambda \, \frac{1}{Z} \frac{\partial^2 Z}{\partial x^2} = \rho_s \cdot c_e \cdot Q \cdot \frac{1}{X} \frac{\partial X}{\partial x} \cdot Z \cdot \frac{q(T_m)}{X} \cdot Z
\]

Assuming that all parameters except \( (x, z) \) are known, the general solution equation of goaf temperature \( T_m \) can be obtained from Formula (3):

Figure 1. Heat dissipation model of floating coal seam

According to the energy conservation equation in the process of heat dissipation of floating coal, the relationship between the temperature of floating coal and the surrounding environmental parameters under the condition of heat balance can be obtained.
The boundary conditions of goaf are as follows:

1. At the position of the working face, the convective heat transfer on the coal surface is strong, and the coal temperature is equal to the airflow temperature on the working face. When \( x = 0 \), \( T_m = T_g \).

2. When the goaf is deeper, the airflow heat transfer in the goaf is smaller, and the heat dissipation of the coal body is mainly through heat conduction. Assuming that the heat generation of coal is uniform in local areas, when \( x / Q \to \infty \):

\[
T_m = T_y + \frac{q(T_m)}{2\lambda_y} \left( \frac{h^2}{4} - z^2 \right) \quad [17]
\]

3. The temperature distribution of coal seams is centrally symmetric, that \( T_m(x, z) = T_m(x, -z) \).

Incorporating the above boundary conditions into formula (4), the solution of \( T_m \) is:

\[
T_m = \left( T_y + \frac{q(T_y)}{T_y + \delta} \right) \sin\left( \frac{\sqrt{\frac{q(T_y)}{T_y + \delta}} \cdot z + \pi}{2} \right)
\]

\[
\cdot e^{-\frac{q(T_y)}{T_y + \delta}} + T_y + \delta
\]

Where

\[
\delta = \frac{q(T_m)}{2\lambda_y} \left( \frac{h^2}{4} - z^2 \right) \quad [7]
\]

3. Calculation of goaf temperature

Based on the energy conservation equations of the oxidation heat generation and heat dissipation process of floating coal, this paper derives the analytical equations of the goaf temperature with respect to \( T_g, T_y, h, q(T), Q, x, \) and \( z \). Therefore, calculating the coal seam temperature \( T_m \) in the goaf is equivalent to calculating the above-mentioned parameter values. The parameter values are shown in Table 1:

| Symbol | Definition and value |
|--------|---------------------|
| \( \rho_g \) | Air density, \( 1.293 \times 10^{-3} \text{g/cm}^3 \) |
| \( C_g \) | Air heat capacity, \( 1.0035 \text{J/g} \cdot \text{°C}^{-1} \) |
| \( C_{o_0} \) | Oxygen concentration of fresh air, \( 9.375 \times 10^{-6} \text{mol/cm}^3 \) |
| \( \lambda_e \) | Thermal conductivity of loose coal, \( 0.92 \times 10^{-3} \text{J/(cm} \cdot \text{s} \cdot \text{°C}) \) |
| \( T_g \) | Air temperature, \( \text{°C} \) |
| \( T_y \) | Coal wall temperature, \( \text{°C} \) |
| \( h \) | Thickness of residual coal in goaf, \( \text{°C} \) |
| \( C_{o_0} \) | Actual oxygen concentration in goaf, \( \text{mol/cm}^3 \) |
| \( q_x(T_m) \) | Oxidizing exothermic strength of floating coal at an oxygen concentration of \( C_{o_0} \), \( \text{J/cm}^3 \cdot \text{s}^{-1} \) |
| \( V_{o_0}(T_m) \) | Oxygen consumption rate, \( \text{mol/s} \cdot \text{cm}^3 \) |
Calculated parameters

**Air leakage intensity of goaf:**

\[ Q(x_i) = \frac{V_0(T_m)(x_{o1} - x_i)}{C_0 \ln \frac{C_i}{C_{o1}}} \]  \[ (8) \]  \[ [19] \]

**Oxidation heat release intensity of residual coal in goaf:**

\[ q(T_m) = \frac{C_{o1}}{C_{o1}} q_0(T_m) \]  \[ (9) \]  \[ [19] \]

Thus, after the laboratory determination of the oxidation heat release strength and oxygen consumption rate of coal samples, the temperature of goaf can be calculated according to the environmental parameters of goaf.

It should be noted that the heat release intensity \( q_0(T_m) \) and oxygen consumption rate \( V_O2(T_m) \) are functions of temperature, and the goaf temperature needs to be calculated by these two parameters, so the independent variables and dependent variables of the equation are functions of each other, it is necessary to gradually obtain the goaf temperature solution through iterative calculation method.

4. Practice test and application

In order to test the calculation method, this method is applied to the 46205 working face goaf of Kaida Coal Mine in Inner Mongolia. The oxidation heat release and oxygen consumption properties of coal samples were experimentally measured, and the temperature of the goaf on the return air side of the 46205 working face was calculated by field environmental parameters, and finally compared with the temperature value obtained by thermistor observation.

4.1. Determination of parameters

The coal sample was collected in May 2019 and tested in the laboratory to obtain the oxidation heat release intensity and oxygen consumption rate of the coal sample. The experimental equipment is shown in Figure 2, and the measurement results are shown in Figure 3. In July 2019, the oxygen concentration in the goaf of 46205 was measured by the buried pipe method, the oxygen concentration in the goaf of the return air side is shown in Figure 4. The temperature of the goaf is measured with a thermistor. The resistance line and the oxygen plastic pipe are protected by a 3-inch steel tube and buried in the goaf along with the working face.

![Figure 2. Experimental setup diagram](image-url)
4.2. Calculation of goaf temperature

The average mining height of the coal seam on the working face of the coal mine is about 2.4m, the coal cutting height is 2m, and the porosity inside the coal seam is about 20%. Then, the floating coal thickness in the goaf is 

\[ h = \frac{(2.4-2)}{(1-0.2)} = 0.5 \text{m}. \]

The air temperature \( T_g \) is 20.21°C, the rock wall temperature \( T_y \) is 13.4°C, and the air density, air heat capacity, and thermal conductivity of loose coal are calculated and plotted according to the values in Table 1. The temperature distribution of goaf is shown in Figure 5.
Figure 5. Temperature distribution of floating coal seam in goaf

Figure 5 shows that the temperature of goaf does not change singly. With the increase of buried depth, the temperature of goaf first increases and then decreases, which is the result of the combined action of air leakage conditions and oxygen conditions in goaf. On the one hand, with the increase of buried depth, the air leakage amount in goaf will decrease, and the heat carried away by airflow will become less, which is conducive to the heat storage of floating coal. On the other hand, the oxygen supply in the deep goaf is insufficient, and the heat generated by oxidation reaction is reduced, so the temperature of coal in the deep goaf is also lower. The central temperature of the coal seam is shown in Figure 6.

Figure 6. Temperature distribution in the center of the coal seam

In order to further verify the prediction results, the calculated goaf temperature (z=0) is compared with the goaf temperature observed by the thermistor. The comparison result is shown in Figure 7:
Figure 7. Comparison of actual goaf temperature and model calculated temperature

It can be seen from the comparison with the actual temperature observation that the calculated goaf temperature value is very close to the actual temperature value, and the temperature change law is the same: with the depth increases, the temperature in the goaf first increases and then decreases. This law is consistent with the temperature measured by Shuguang, J. [20] and Shi, G.Q. [21] in Sanhejian mine and Donghuantuo mine.

After analysis, the average relative errors between the calculated temperature value and the observed value are 6.07% and 10.14% respectively, and the calculated results can meet the requirements of practical application, the calculation results are shown in Table 2. In addition, the prediction of high-temperature areas in goaf is also accurate. The highest temperature of coal is predicted to be 27.11°C and buried 25m in the goaf, which is the same as the observation. It can be seen that this model can reflect the temperature distribution of goaf and provide help for disaster prevention and control.

Table 2. Error analysis of model and experiment

|                        | the average relative errors | The highest temperature | The high temperature area |
|------------------------|-----------------------------|--------------------------|--------------------------|
| Calculated value       | --                          | 27.11°C                  | 25m                      |
| Measurement point 1    | 6.07%                       | 27.5 °C                  | 21m                      |
| Measurement point 2    | 10.14%                      | 25.6 °C                  | 34m                      |

Further analysis showed that the predicted values were generally higher than the observed values, possibly due to the difficulty in controlling the position of thermistors buried in the goaf, and the temperature at the edge of the coal seam is lower. Another reason may be that the floating coal temperature in goaf is still in the development stage, and the floating coal temperature does not reach the maximum value, so the observed value is lower than the calculated temperature.

5. Conclusion

(1) According to the energy conservation equation of the heat generation and heat dissipation process of floating coal, the analytical solution of the temperature field equation of goaf is derived in this paper, so that the temperature of floating coal seam in goaf can be calculated and analyzed.

(2) Although there are some errors between the calculated temperature and the actual temperature, the accuracy can meet the requirements of practical application. In the calculation example, the average relative error between the calculated temperature value and the observed value is about 10%, and the calculated results can provide guidance for the prevention and control of coal spontaneous combustion in goaf.

(3) With the increase of buried depth, the floating coal temperature in the goaf of kaida Coal Mine 46205 first increased and then decreased. It was calculated that the highest temperature in the goaf was 27.11°C, which was located about 25m deep in the goaf.

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