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A Method for Detection of Fire Source Positions in High-Temperature Areas

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ABSTRACT

Spontaneous combustion of coal is an important disaster that needs to be addressed in the coal mine production process. Since its ignition position is often unknown and concealed, determining the ignition position in the goaf is of great significance to the work safety of the mining area. This study measured the thermal conductivity of coal samples using the spherical thermal conductivity model, and obtains the fitting relationship between the thermal conductivity, the heating voltage U and the inner sphere outer wall temperature t1 by inputting different voltages, and the correlation coefficient R2 was all greater than 0.99. Through analysis of the spherical geometric model, it was determined that the ignition point was at the vertical depth of 16.542m from the highest temperature point in the goaf, and that the distance from the ignition position to the ignition source ranged between 13.49m to 1.03m when the temperature in the goaf was 60°C to 1700°C. Through comparison with the actual data, the error was found to be 4.7%, indicating that the proposed model was more accurate. Finally, it was found that the thermal conductivity of coal is closely related to the porosity, degree of metamorphism and inhomogeneity of the medium.

1. INTRODUCTION

As a primary energy, coal has always been an important source of energy for industrial production in various countries. At present, the import and export of coal and the development of the coal industry has been slowing down in China due to the impact of the pandemic and the overcapacity of coal production, but China's energy demand is still huge. According to statistics (Figure 1), among the primary energy consumption in China, from 2009 to 2019, coal was still occupying the dominant position [1-3]. Therefore, how to carry out production safely and efficiently and handle various incidents conveniently and quickly has become particularly important. In the process of coal mining, the spontaneous combustion of coal is one of the main disasters that often occur [4, 5]. Therefore, it is the top priority to address spontaneous combustion incidents downhole [6-10].

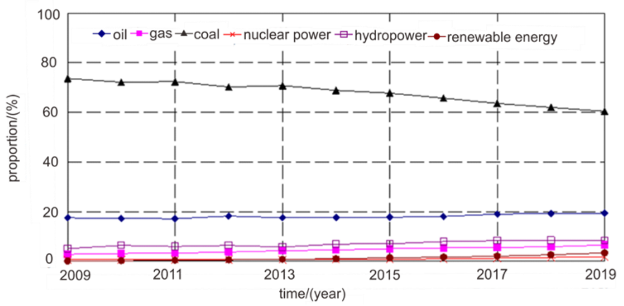


Figure 1. Statistical chart of China's primary energy consumption structure from 2009 to 2020

Among the many areas subject to spontaneous combustion of coal, goafs always suffered the most serious fires. During the advancement of the working face, the position of the broken coal in a goaf may differ, so the areas prone to spontaneous combustion of coal may also vary [11, 12]. However, judging from the current monitoring methods, it is difficult to accurately determine the position of the fire source and the position of the high temperature area [13]. At present, the methods to locate fire sources studied at home and abroad mainly include magnetic field detection, resistance detection, electromagnetic wave detection, gas detection and temperature detection methods. Among them, the temperature detection method is the most direct testing method for spontaneous combustion of coal, but when the temperature of the ignition source is relatively low, the measurement error will be relatively large. Therefore, there are still great challenges in the detection of hidden fire sources in goafs, and this subject needs to be further explored.

The spontaneous ignition in the goafs is often unknown and concealed, so it is impossible to directly locate it and identify its intensity, but through acquisition of information and establishment of a mathematical model, we may be able to do so. Therefore, it is necessary to invert the temperature field of the fire source, that is, to calculate local parts from the whole, and find the essential cause from the phenomena [14, 15]. Before a mathematical model is established, the thermal conductivity of coal samples in the mining area should be measured first. At present, the commonly used measurement methods include the horizontal plate method, the cylinder method [16], the hotline method [17, 18] and the concentric sphere method [19, 20]. In this study, the concentric sphere method was used to measure the thermal conductivity of coal samples, and a mathematical model was established to simulate, predict and analyze the spontaneous combustion of coal in the high-temperature area of a goaf, so as to locate the ignition point in the goaf area and provide a theoretical basis for the selection of fire prevention and extinguishing schemes in mining areas.

2. PROFILE OF THE RESEARCH AREA

This study was mainly intended to predict the ignition point in the high-temperature area in the goaf of a mining area in Xinjiang, and to provide a feasible fire prevention and fighting scheme. According to the analysis of the results of the fifth coal field fire zone survey in Xinjiang, by the end of 2019, the fire zones in Xinjiang covered a total area of 4.7773 million m^2, causing a huge coal loss and resulting in an economic loss of 2 billion RMB [21]. In addition, coal combustion will produce a large amount of toxic and harmful gases, which will destroy land and grassland, and may cause forest fires [22]. Table 1 shows the proportions of coal field fire zones in the cities and prefectures of Xinjiang. The main causes of fires in Xinjiang coalfields are related to the distribution of coal seams and their occurrence conditions [23, 24].

Table 1. Proportions of the coal field fire zones in various cities of Xinjiang (according to the fifth coal field fire zone survey in Xinjiang, 2019)

No.	Prefecture name	Number of fire zones	Area of the fire zones /10,000m^2	Proportion in terms of area /%
1	Jichang	18	261.54	54.75
2	Turpan	7	90.99	19.05
3	Yili	4	39.10	8.18
4	Hami	3	30.76	6.44
5	Urumchi	4	24.64	5.16
6	Tacheng	2	22.06	4.62
7	Aksu	1	7.55	1.58
8	Bazhou	1	1.10	0.23

3. EXPERIMENTAL METHODS AND CONDITIONS

The distribution of spontaneous combustion sources in the goaf depends on the distribution of residual coal deposits and air leakage positions. The shapes of the ignition sources are unknown, which may be affected by the distribution of the residual coal and the degree of fragmentation and compactness of the caving rocks, so the ignition sources are regarded as point-type sources. The spherical thermal conductivity model was first established, as shown in Figure 2. Without the fire source scope considered, it is assumed that there is a single fire source, which is located at the center of the spherical model, and that the medium near the high-temperature fire source in the goaf is uniform and isotropic, with the heat conducted evenly outwards. Based on the Fourier's law of heat conduction and known conditions, an equation was established, which inversely solved the distance from the fire source to the wall. Then it was necessary to obtain the thermal conductivity of the coal seam. The sphere method was used to measure the thermal conductivity of the thermal insulation material. Based on the different input voltages, the temperatures of the outer wall of the inner sphere and the inner wall of the outer sphere were measured to obtain the thermal conductivity of the material, which was substituted into the equation to obtain the position and intensity of the fire source.

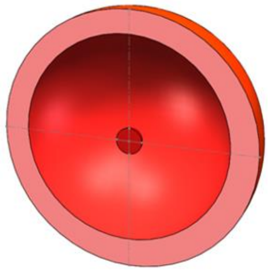


Figure 2. Model of the point-type fire source

The next step was to check the experimental equipment. Since the inner and outer balls are completely concentric, the test piece was homogeneous, and the surface temperatures of the inner and outer balls are uniform. In this experiment, the natural convection state of the outer spherical shell was kept stable. A one-dimensional steady-state temperature field was established inside the test piece, and the Fourier's law of heat conduction was applied to the thermal conduction process of the sphere walls. The experimental conditions for measuring the thermal conductivity are shown in Table 2.

Table 2. Experimental conditions for measuring the thermal conductivity of the granular material by the sphere method

Coal sample quality /g	Inner sphere volume /cm^3	Outer sphere volume /cm^3	Coal sample density /(g/cm^3)	Coal sample porosity /%
2208.48	221	2810	0.853	36.34

4. ANALYSIS OF EXPERIMENTAL RESULTS

4.1 Experimental data processing

Suppose that the inner and outer surface temperatures of the sphere wall are maintained at t_1 and t_2, respectively, and remain constant. Apply the Fourier's law of heat conduction to the heat conduction process of the sphere wall to obtain Eq. (1) [15, 20],

$$Q = -\lambda F \frac{dt}{dr} = -\lambda 4\pi r^2 \frac{dt}{dr} \quad (1)$$

When the boundary condition is $r=r_1$, $t=t_1$; when $r=r_2$, $t=t_2$. Substitute the integral of Eq. (1) into the boundary condition to obtain Eq. (2):

$$\lambda_m = \frac{Q\delta}{\pi d_1 d_2 (t_1 - t_2)} \quad (2)$$

where, λ_m - thermal conductivity of the material between the sphere walls when $t_m=(t_1+t_2)/2$, $W/(m\cdot°C)$; Q - quantity of electric heat, W; δ - material thickness between the sphere walls, $\delta = (d_1-d_2)/2$, m.

After the power is turned on, the quantity of the electric heat can be calculated from the heating voltage, current and heating time, as shown in Eq. (3):

$$Q = \bar{U} \cdot \bar{I} \cdot T/60 \quad (3)$$

where, $\bar{U}$- mean value of the actual voltage, V; $\bar{I}$- mean value of the actual current, A; T-actual heating time, s.

Suppose that the thermal conductivity has a certain functional relationship with the temperature, that is, $\lambda=f(t)$. Use the spherical method to measure the thermal conductivity of the thermal insulation material, and change the heating voltage, with 25V as the starting point in the first group and at a gradient of 5V per change. Add another 5V to the starting point for each of the other groups successively. The calculated data of the thermal conductivity under different heating voltages are shown in Table 3.

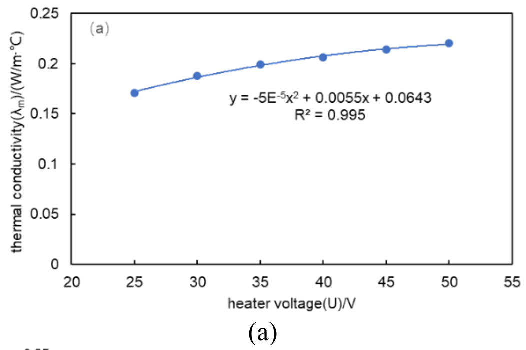
Table 3. Values of parameters under different heating voltages

Heating voltage/V	Average voltage/V	Average current/A	Outer wall temperature of the inner ball t_1/°C	Inner wall temperature of the outer ball t_2/°C	Heating time T/s
25	29.75	0.1	35.5	28.0	32
30	25.97	0.1	37.6	28.1	51
35	34.14	0.1	40.8	28.6	55
40	35.27	0.1	43.3	29.0	62
45	37.60	0.1	45.7	29.6	68
50	39.57	0.1	47.9	30.7	71

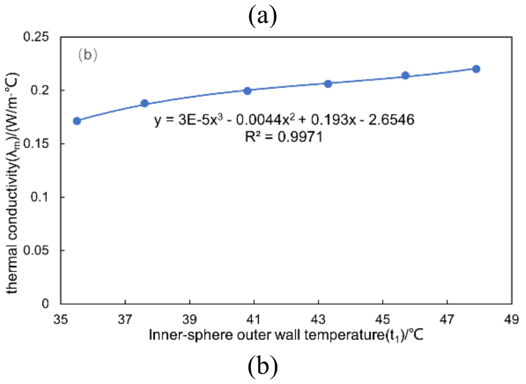
4.2 Analysis of experimental data

4.2.1 Relationships between thermal conductivity and heating voltage U and outer wall temperature t_1 of the inner ball

The fitting relationships between the thermal conductivity and the heating voltage U and the outer wall temperature t_1 of the inner ball are shown in Figure 3. It can be seen from Figure 3a that there is a linear relationship between the thermal conductivity and the heating voltage U, from which, the fitting function y=-5E$^{-5}x^2$+0.0055x+0.0643, and the correlation coefficient R^2=0.995 can be obtained; it can be seen from Figure 3b, there is also a linear relationship between the thermal conductivity and the outer wall temperature t_1 of the inner ball, from which the fitting function y=3E$^{-5}x^3$-0.0044x^2+0.193x-2.6546, and the correlation coefficient R^2=0.9971 can be obtained. The correlation coefficients R^2 of both the two variables are greater than 0.99, showing a good linear relationship and fitting degree.



(a)



(b)

Figure 3. Fitting relationships between the thermal conductivity and the heating voltage U (a) and the outer wall temperature t_1 of the inner ball (b)

4.2.2 Determination of fire zone positions and temperatures and division of fire zones

The change of temperature in the temperature field of the same isothermal surface in the spherical model can be expressed by the formula of Fourier's law:

$$Q = -A\lambda \frac{t_1 - t_2}{\sigma} \quad (4)$$

where, Q - heat, W; A - unit area; λ- thermal conductivity of the coal body; t_1 and t_2 - temperature at the two points; σ - distance between the two points.

Inder the sphere model, the temperature distribution on any flat wall outside the coal seam is annular, and the temperature in the center of the ring decreases along the radial direction towards the outside of the ring. The center of the fire source is at a vertical distance from the center of the flat wall with the highest temperature. As shown in Figure 4, suppose that when the temperature is t_1, the distance between this position and the fire source is r_1, and that the temperatures taken at the two points with the same interval L from the position of t_1 along a straight line are t_2 and t_3, then according to the geometric relationship, there are:

$$r_1^{\,2} + L^2 = r_2^{\,2} \quad (5)$$

$$r_1^{\,2} + 4L^2 = r_3^{\,2} \quad (6)$$

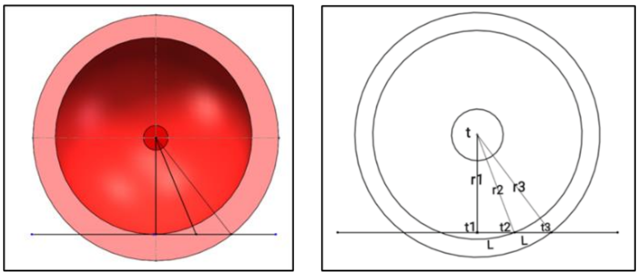
Combine the boundary conditions and Eq. (2), (5) and (6), and there is:

$$\lambda = \frac{Q(r_m - r)}{4\pi r r_m \Delta t} \quad (7)$$

It can be seen from Figure 4 that, ideally, the maximum temperature should be at the center of the flat wall, which is the closest to the fire zone, and vertically, this position points inwardly to the fire zone. According to the actual situation of the mine area, all position points are shown in Table 4. It can be seen that the fire source point is at a vertical depth of 16.542m from the point with the highest temperature.

Table 4. Actual positions of the mine

L/m	r_1/m	t_1/°C	r_2/m	t_2/°C	r_3/m	t_3/°C
2	16.542	35	16.663	34.2	17.019	31.9



(a) (b)

Figure 4. (a) Diagram of the 2D geometric model; (b) Diagram of the calculation model

Substitute t_1, t_2 and t_3 into Eq. (7), and simplify the equation to obtain:

$$\begin{cases} \frac{(r_1 - r)}{r_1(\mathrm{t} - \mathrm{t}_1)} = \frac{(r_2 - r)}{r_2(\mathrm{t} - \mathrm{t}_2)} \\ \frac{(r_1 - \mathrm{r})}{r_1(\mathrm{t} - \mathrm{t}_1)} = \frac{(r_3 - r)}{r_3(\mathrm{t} - \mathrm{t}_3)} \end{cases} \quad (8)$$

Suppose that the temperature of the goaf reaches the critical temperature of coal at 60℃, the distance between this position and the fire source is 13.49m by calculation; similarly, assuming that the temperature of the goaf reaches the coal combustion temperature at 1700℃, then the distance between the position and the fire source is 1.03m by calculation.

4.2.3 Model test

The relationship between the temperature *t* and the fire zone radius *r* can be expressed by Eq. (8):

$$t = -\frac{r_1 r_2}{r_1 - r_2}\frac{1}{r}(t_1 - t_2) + \frac{r_1 t_1 - r_2 t_2}{r_1 - r_2} \quad (9)$$

Through comparison of the theoretically analyzed data with the actual measured data, a test function was established using the relative standard deviation method:

$$\eta = \frac{\sqrt{\frac{\sum_{i=1}^{n}(t_i - t_0)^2}{n}}}{t_0} \quad (10)$$

where, t_i - the actual measured temperature of the i-th group; t_0 - the theoretically calculated temperature.

Substitute the data, and through calculation, η=0.047, that is, the error is 4.7%, which is small, indicating that the proposed model is accurate.

5. ERROR ANALYSIS

(1) Error analysis of thermal conductivity

According to the fitting relationship between the thermal coefficient and the heating voltage U and the outer wall temperature t_1 of the inner ball, the average thermal conductivity of the selected study area at 44℃ is λ=0.21(W/m·℃), which is within the theoretical range of [0.21, 0.27] (W/m·℃), and the correlation coefficient R^2 is greater than 0.99, so there is a good linear relationship based on the experimental results. This shows that the main reason for the experimental error may be the system error, such as the inaccuracy of the system parts (e.g., ammeters and voltmeters), which results in errors of the test data; or the small temperature differences between the sphere shells, etc.

(2) Error analysis of the fire source positioning model in the high temperature area

Through analysis of the calculation results of the fire source positioning model, it can be seen that there is a certain deviation from the actual situation, which may result from the following reasons:

1) Model error

In the sphere shell model, in order to simplify the problem and reduce the difficulty of calculation, the changes in density and porosity of the coal body around the fire source and those in the thermal conductivity of substances resulting from temperature changes were all ignored, and the broken coal body was regarded as a homogeneous medium. Since the model and algorithm were simplified, there were deviations from the actual situation, which resulted in the inconsistency between the model results and the actual situation.

2) Observation error

The thermal conductivity in this experiment was measured using the sphere shell method. The data in the calculation formula were all recorded and processed manually, in which, the observation errors were accumulated, which contributed to the errors in the final model results.

3) Rounding error

The result of this experimental model was calculated by the computer, but the calculation was not run for hundreds or thousands of times. Although the result was not "lost", the error generated cannot be ignored.

6. INFLUENCING FACTORS TO THE THERMAL CONDUCTIVITY OF COAL

In the actual situation, the thermal conductivity of coal varies greatly with the environment and its own properties [25-27], while in the model, it is impossible to accurately calculate each discrete point, so it is necessary to analyze the influencing factors to the thermal conductivity of coal.

(1) Effect of porosity on the thermal conductivity of coal

Coal bodies have different porosity. When any gas is filled into the pores, the thermal conductivity of the test block will decrease due to the small thermal conductivity of the gas. So the larger the porosity and the higher the temperature, the smaller the thermal conductivity.

(2) Effect of coal metamorphism on the thermal conductivity of coal

The thermal conductivity of coal is closely related to the composition of coal (volatile matters, moisture, and ash, etc.), and the latter also has something to do with the degree of metamorphism of coal. For example, when the volatile content of coal is high, the degree of metamorphism of coal will be low, and its thermal conductivity will be high; similarly, when the ash content of coal is high, the degree of metamorphism of coal will be low, and its thermal conductivity will be high.

(3) Effect of uneven medium on the thermal conductivity of coal

Compared with polycrystalline substances, monocrystalline substances have a slightly larger thermal conductivity. The crystal structure of coal seam is complex, so its thermal conductivity is small. The more complex the chemical composition of the coal seam, the more impurities, or the more solid solutes formed after impurities are added, and the smaller the thermal conductivity. This is because the addition of impurities and the formation of solid solutes can easily distort and dislocate the crystal lattices, destroy the integrity of the crystal, and make the crystal structure more complex, and accordingly, the thermal conductivity is slightly low.

7. CONCLUSIONS

This study mainly simulated and predicted the ignition point in a high-temperature area by establishing a mathematical model, so as to determine the conditions for the spontaneous ignition of coal in goafs, and provide a basis for the prevention and control of spontaneous combustion of coal and fires in the mining area.

(1) The thermal conductivity of coal samples was determined using the system device of the sphere thermal conductivity model, and the fitting relationships between the thermal conductivity and the heating voltage U and the outer wall temperature t_1 of the inner sphere were established.

(2) Through analysis of the spherical geometric model, the fire zone positions and range of the goaf within the coal spontaneous combustion temperature range were determined, and the accuracy of the model was tested.

(3) Based on the actual situation, the effects of porosity, metamorphism degree and medium inhomogeneity on the thermal conductivity of coal were analyzed.

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