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Multi-index Fusion Prediction at Various Stages for Coal Spontaneous Combustion

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Coal spontaneous combustion fire seriously threatens the safety of mine production. How to improve the prediction accuracy of coal spontaneous combustion is a hot topic in current research. The critical temperature point of coal spontaneous combustion and the temperature point of C2H4 occurrence were determined by the temperature-programmed oxidation simulation experiment of coal spontaneous combustion. Taking the reliability of each prediction index as the weight and introducing the error weakening factor, the multi-index fusion prediction model of coal spontaneous combustion was constructed, and the multi-index fusion prediction method of coal spontaneous combustion was put forward. The multi-index fusion prediction method can significantly improve the accuracy of coal spontaneous combustion prediction. The research method can provide theoretical guidance for the prevention of mine fire.

Introduction

Coal spontaneous combustion is one of the main disasters in mines (Wang, 2008). Literature (Wang et al., 2018; Deng et al., 2014) through the qualitative analysis of each composite index in the process of coal spontaneous combustion and the optimization of each index, the prediction index system of coal spontaneous combustion was established. In order to predict the spontaneous combustion temperature of coal more accurately, the literature (Cao et al., 2017; Zhu et al., 2015) established the prediction equations of the spontaneous combustion temperature of gas coal and bituminous coal respectively by fitting the ratio of CO2 and CO concentration with the coal temperature.

This paper analyzed the simulation experiment of coal spontaneous combustion on 1029 sinking and drifting face of No.12 coal seam in Linnancang Colliery. According to the variation law of each index gas with temperature, the critical temperature point of coal spontaneous combustion and the temperature point of C2H4 occurrence were determined, and then the oxidation stages of coal spontaneous combustion were divided. Based on the basic principle of least squares method, the forecasting indicators of coal temperature were functionalized in each stage, and the grey comprehensive correlation analysis method was used to calculate the reliability of the forecasting indicators in each prediction stage, then the error weakening factor was introduced to construct the multi-index fusion prediction model of coal spontaneous combustion. In the end, the multi-index fusion prediction method of coal spontaneous combustion was proposed to improve the prediction accuracy of coal spontaneous combustion (Rambha and Ren, 2018).

Simulation experiment of coal spontaneous combustion oxidation

Coal samples were collected from 1029 sinking and drifting face of No.12 coal seam in Linnancang Colliery. The coal samples were mixed fully to eliminate the particularity of coal samples. Because the particle size has a great influence on spontaneous combustion of coal (Xie et al., 2003), in order to make the experimental coal sample closer to the real situation of the mine,500g coal samples were taken at random each time and five times of repeated screening were carried out on the coal sample. Each coal sample was screened out into five stages (0-1mm, 1-2mm, 2-4mm, 4-8mm, 8-20mm) with particle size and the quality of each coal was weighed in five stages, then the quality of each coal sample was calculated. The proportion of coal particles in each

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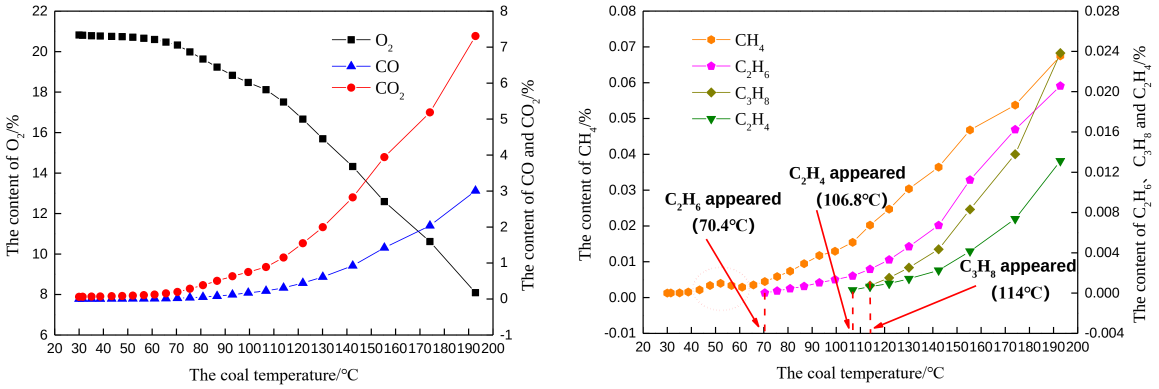
stage of the sample to the mass of the whole coal sample was calculated, and the distribution ratio of coal particle size in 1029 sinking and drifting face of No.12 coal seam in Linnancang Colliery was obtained by solving five groups of average values. According to the size distribution of the coal in 1029 sinking and drifting face of No.12 coal seam in Linnancang Colliery, the experimental coal sample was obtained.

The process of coal spontaneous combustion was simulated by the temperature-programmed system (the flow rate of compressed air was 100 ml/min and the heating rate was 0.5 ºC/min). In order to more comprehensively characterize the relationship between the index gases and coal temperature, gas chromatograph (KSS-5690A) was used to monitor the index gases at equal time interval (gas was collected every 10 minutes from 30 ºC to 200ºC) by external standard method.

Division of oxidation stages of coal spontaneous combustion

1.1 Indicator gas analysis

Through the simulation experiment of coal spontaneous combustion oxidation, it was found that CO, CO_2, CH_4, C_2H_6, C_3H_8 and C_2H_4 gases were produced during the coal spontaneous combustion oxidation process at 30 ºC ~192.8 ºC, accompanied by the consumption of O_2. The variation curves of gas composition content with coal temperature are shown in Figure 1.



(a) Non-hydrocarbon gases (b) Hydrocarbon gases

Figure 1: The variation curves of gases with coal temperature during spontaneous combustion of coal

The law of non-hydrocarbon gases changing with coal temperature is obtained from Figure 2 (a). The law of hydrocarbon gases changing with coal temperature is obtained from Figure 2 (b). Therefore, CH_4 gas can not be used as a composite index factor for predicting coal spontaneous combustion. When C_2H_4 occurs, small molecules such as side chains and bridge bonds in the internal structure of coal begin to crack (Qin et al., 2010), and there is no C_2H_4 gas in the coal itself, so it can be used as the marker gas for coal spontaneous combustion to enter the stage of severe oxidation.

1.2 Determination of critical temperature

In the process of coal spontaneous combustion, the characteristic temperature corresponding to the intensification of oxygen consumption and the acceleration of chemical reaction is the critical temperature. Determining the critical temperature of coal spontaneous combustion plays an active guiding role in the safe production of coal mine, the prediction of coal spontaneous combustion and fire prevention. The process of temperature-programmed oxidation of coal spontaneous combustion has the following relation:

$$\ln \varphi_{\text{out}} = -\frac{E_a}{RT} + \ln \frac{mnASLV_m c_{O_2}^N}{Q} \tag{1}$$

It can be seen from the above formula that when the flow rate of gas supply is constant, lnφ_{out} and (-1/T) should have a linear relationship in different oxidation stages. The critical temperature point can be determined by analyzing the linear fitting intersection point between lnφ_{out} and (-1/T) in the process of coal spontaneous combustion. As shown in Figure 2, the critical temperature of coal spontaneous combustion from slow oxidation stage to accelerated oxidation stage is 60.4 ºC.

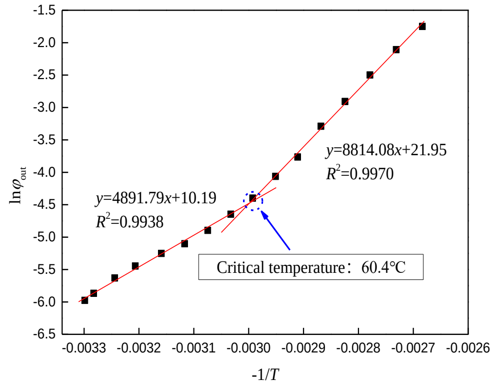


Figure 2: The relation between lnφout and (-1/T) in coal spontaneous combustion process

1.3 Determination of temperature range at different stages of coal spontaneous combustion

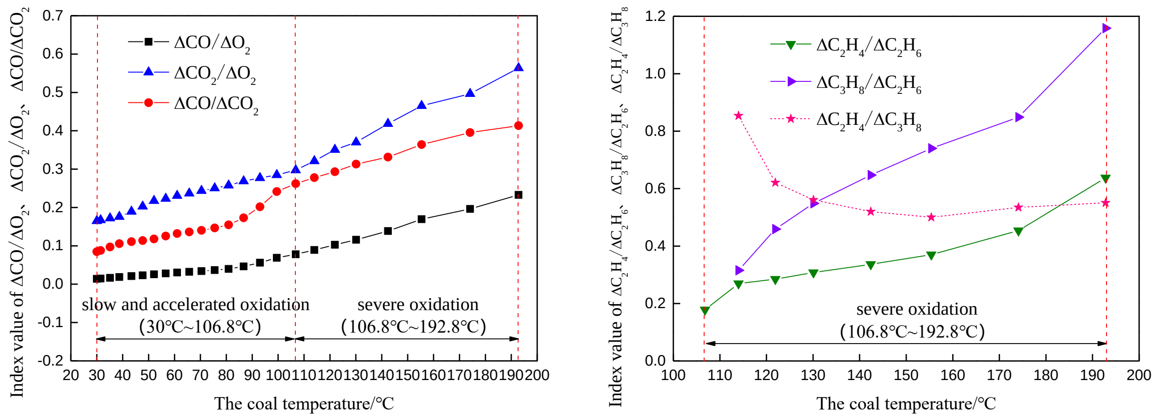
According to the critical temperature point and the temperature point of C_2H_4 occurrence, the process of coal spontaneous combustion was divided into three stages: slow oxidation, accelerated oxidation and severe oxidation. The temperature range of each stage is detailed in Table 1.

Table 1: Temperature range of coal spontaneous combustion at different stages

Spontaneous combustion stage	Slow oxidation	Accelerated oxidation	Severe oxidation
Temperature range/°C	30.0~60.4	60.4~106.8	106.8~192.8

1.4 Prediction index of coal spontaneous combustion at different stages

The prediction of coal spontaneous combustion should try to eliminate the impact of air volume change. Therefore, in this paper, the ratio of the change of homogeneous gas is taken as the prediction index of coal spontaneous combustion,such as Graham index ($\Delta CO/\Delta O_2$, $\Delta CO_2/\Delta O_2$ and $\Delta CO/\Delta CO_2$),allane ratio ($\Delta C_2H_4/\Delta C_2H_6$, $\Delta C_2H_4/\Delta C_3H_6$) and chain alkanes ratio ($\Delta C_3H_8/\Delta C_2H_6$). The variation curves of indicators with coal temperature are shown in Figure 3.



(a) Non-hydrocarbon indicators (b) Hydrocarbon indicators

Figure 3: The variation curves of indicators with coal temperature during coal spontaneous combustion

According to the analysis of Figure 3 (a), $\Delta CO/\Delta O_2$, $\Delta CO_2/\Delta O_2$ and $\Delta CO/\Delta CO_2$ increase monotonously with the increase of coal temperature in the prediction stage. In the severe oxidation stage, the index gases of coal spontaneous combustion are CO, CO_2, C_2H_6, C_2H_4 and C_3H_8, accompanied by oxygen consumption. Combining with the analysis of Figure 3 (a) (b), shows that, in addition to$\Delta C_2H_4/\Delta C_2H_6$, other indicators increase monotonously with the increase of coal temperature in the prediction stage.

Prediction method of coal spontaneous combustion

1.5 Establishment of prediction equation for coal temperature at different stages

The least square principle of curve fitting can be described as: according to the known data set (x_i, y_i)(i=1, 2, …, n), an approximate function is selected to minimize the sum of squares of errors between all data points and fitting points:

$$\sum_{i\ 1}^{n}\delta_i^2=\sum_{i=}^{n}[y_i-\varphi(x_i)]^2=min \qquad (2)$$

In the formula, y_i is the data point; $\varphi(x_i)$ is the fitting point; δ_i is the error of data point and fitting point.
Although the forecasting indicator is continuous in the process of coal spontaneous combustion, based on the basic principle of least square method, the simulation experimental data of coal spontaneous combustion should be functionalized in various stages to make the prediction equation more accurate. Taking C_2H_4 as the marker gas of coal spontaneous combustion entering the stage of severe oxidation, the coal spontaneous combustion is divided into two prediction stages. The coal temperature of each prediction stage is taken as the ordinate, and the forecasting indicator value is fitted with the abscissa. The best equations of fitting degree R^2 and overall trend are selected as the prediction equation for coal temperature in corresponding prediction stage.

1.6 Calculation of prediction indicators confidence level at various prediction stages

The grey comprehensive correlation analysis method is used to calculate the grey comprehensive correlation degree between coal temperature and forecasting indicator in each stage of coal spontaneous combustion (Zhu, et al., 2008). The grey comprehensive correlation degree between coal temperature and forecasting indicator is to measure the degree of synchronous change between coal temperature and forecasting indicator according to the similarity or difference of the overall development trend between them. Its value can be regarded as the credibility of forecasting indicator (Deng et al., 2011), that is, the grey comprehensive correlation degree is greater, this indicates that the closer the index is to coal temperature, the higher the credibility of the corresponding coal temperature prediction value.
The forecasting indicator I_1 in the temperature range of 106.8ºC ~192.8ºC (severe oxidation stage) is taken as an example.
(1) The isochronal coal temperature in this stage is taken as the system reference sequence X_0, and the corresponding index I_1 of each temperature point is the system comparison sequence X_1.
X_0=[x_0(1), x_0(2), …, x_0(8)]=(106.8,114.0121.9,130.1,142.4,155.4,174.1,192.8)
X_1=[x_1(1), x_1(2), …, x_1(8)]=(0.07794,0.08925,0.10277,0.11586,0.13861,0.16933,0.19631,0.23297)
(2) The geometric similarity degree of broken line between coal temperature and forecasting indicator (grey absolute correlation degree) is calculated.
First, obtaining the initialization like $X_i^{'0}$:
X_0^0=(0,7.2,15.1,23.3,35.6,48.6,67.3,3.86)
X_1^0=(0,0.1131,0.02484,0.3792,.06067,0.09139,0.11838,0.15504)
Then, calculating correlation coefficient:

$$s_0=\sum_{k=2}^{7}x_0(k)+\tfrac{1}{2}x_0^0(8)=240.1,\ \ s_1=\sum_{k=2}^{7}x_1(k)+\tfrac{1}{2}x_1^0(8)=0.42203$$

$$s_1-s_0=\sum_{k=2}^{7}[x_1^0(k)-x_0^0(k)]+\tfrac{1}{2}[x_1^0(8)-x_0^0(8)]=239.678$$

At last, calculating grey absolute correlation degree:

$$\varepsilon_{01}=\frac{1\quad |s_0|+|\quad|}{1+|s_0|+|s_1|+|s_1-s_0|}\quad 0.502$$

(3) The approximate degree of change rate between coal temperature and forecasting indicator (grey relative correlation degree) is calculated.
First, obtaining the initialization like $X_i^{'0}$:
$X_0^{'0}$=(0,0.06742,0.14139,0.2116,0.3333,0.45505,0.63015,0.8024)
$X_1^{'0}$=(0,0.14516,0.31871,0.48657,0.77852,1.17264,1.17264,1.51892,1.98928)
Then, calculating correlation coefficient:

$$s_0^{'}=\sum_{k=2}^{7}\ {}_0^{'0}(\ \ )+\tfrac{1}{2}x^{'0}(8)=2.24813\ ,\ \ s_1^{'}=\sum_{k=2}^{7}\ {}_1^{'0}(\ \ )+\tfrac{1}{2}x^{'0}(8)=5.41516$$

$$s_1^{'} - s_0^{'} = \sum_{k=2}^{7}[x_1^{'0}(k) - x_0^{'0}(k)] + \tfrac{1}{2}[x_1^{'0}(8) - x_0^{'0}(8)] = 3.16704$$

At last, calculating grey relative correlation degree:

$$r_{01} = \frac{1+|s_0| \quad |\ ^{'}|}{1+|s_0^{'}|+|s_1^{'}|+|s_1^{'}-s^{'}|} \quad 0.732$$

(4) The grey comprehensive correlation degree is calculated.

$$\rho_{0i} = \theta\varepsilon_{0i} + (1-\theta)r_{0i}$$

Where θ is correlation coefficient, θ∈[0,1], usually θ=0.5.

$$\rho_{01} = 0.5(\varepsilon_{01} + r_{01}) = 0.5 \times (0.502 + 0.732) = 0.617$$

Using the grey comprehensive correlation analysis method takes into account two aspects: (1) This method not only pays attention to the similarity degree of the broken line between the coal temperature and the prediction index, but also to the approximation degree of the change rate between them. The grey comprehensive correlation degree obtained is the quantity that comprehensively represents the close degree between the coal temperature and the forecasting indicators; (2)This method does not have integrity, that is, the grey comprehensive correlation degree obtained only indicates the correlation degree between coal temperature and a specific prediction index, and its value has nothing to do with other forecasting indicators. Based on this, the grey comprehensive correlation analysis method can provide parameters for the subsequent introduction of error weakening factors and the construction of multi-index fusion prediction model, so that the staged prediction method and multi-index fusion prediction model can be organically combined. The reliability of forecasting indicators of coal spontaneous combustion in each prediction stage is shown in Table 2.

1.7 Construction of multi-index fusion prediction model

Considering the difference between the actual coal particle size and the diffusion of gas molecules in the air and the simulation experiment, the predicted value of coal temperature may fluctuate around the actual value. In order to further improve the accuracy of coal spontaneous combustion prediction and prevent the occurrence of false alarm, based on the fact that the grey comprehensive correlation degree is not holistic, the reliability of each prediction index is taken as the weight, and the error weakening factor is introduced to balance the prediction error, and then the multi-index fusion prediction model of coal spontaneous combustion is constructed.

(1) Normalization of the credibility corresponding to forecasting indicators is used to get the error weakening factor.

$$\omega_i = \frac{\rho_i}{\sum_{j=1}^{n}\rho_j} \quad \frac{\rho_i}{\rho_1 + \rho \quad + \ldots + \rho_i + \ldots + \rho} \tag{3}$$

In the formula, w_i is the error weakening factor corresponding to the No.*i* prediction index in the prediction stage of coal spontaneous combustion; ρ_i is the reliability corresponding to the No.*i* prediction index in the prediction stage of coal spontaneous combustion; ρ_j(=1, 2, …, *i*, …, *n*) is the reliability corresponding to the No.*j* prediction index in the prediction stage of coal spontaneous combustion.

(2) Introducing the error weakening factor, fusing the each prediction equation of coal temperature, and then the multi-index fusion prediction model is constructed.

$$\mathrm{T} = R_{\omega} \cdot R_t = \sum_{i=1}^{n}\omega_i t_i \tag{4}$$

In the formula, T is predicted coal temperature, °C; R_w is error weakening factor set, $R_w=(w_1, w_2,\ldots, w_n)$; R_t is prediction equation set of coal temperature, $R_t=(t_1, t_2,\ldots, t_n)^T$; t_i(i=1, 2, .., n) is the prediction equation of coal temperature corresponding to the No.*i* prediction index in the prediction stage of coal spontaneous combustion, °C.

1.8 Prediction guidance scheme of coal spontaneous combustion

Using bundle tube monitoring system to collect downhole gas and detect its composition and content, the prediction guidance scheme of coal spontaneous combustion is as follows: (1) After calculation, if there is no marker gas generated, then there is no spontaneous combustion of coal at this time. (2) If CO gas is found but no C_2H_4 gas is found, then determining whether the indicator is abnormal according to the calculation result of composite index value: if the composite index value meets the corresponding range of the index in Table 2, the reliability of the index is the corresponding value in Table 2; if not, it indicates that the index is abnormal and its reliability is 0. Finally, the index value and its corresponding credibility are substituted into the multi-index fusion prediction model to calculate the coal temperature and the stage of coal spontaneous combustion is determined, and then the corresponding fire prevention measures are taken. (3) If C_2H_4 gas is found, the spontaneous combustion of coal is in the stage of severe oxidation. Similarly, according to the scheme (2), the temperature of coal is predicted and the corresponding intensity of fire prevention measures are taken.

Conclusion

According to the critical temperature point and the temperature point of C_2H_4 occurrence under the temperature-programmed oxidation, the process of coal spontaneous combustion can be divided into slow oxidation stage, accelerated oxidation stage and severe oxidation stage.

In the slow oxidation stage and the accelerated oxidation stage, I_1, I_2 and I_3 are the suitable indicators for the prediction of coal spontaneous combustion. In the severe oxidation stage, I_1-I_5 is the suitable indicators for the prediction of coal spontaneous combustion.

The grey comprehensive correlation analysis method was used to obtain the reliability of the forecasting indicators in each prediction stage. Taking the reliability as the weight and introducing the error weakening factor, the multi-index fusion prediction model of coal spontaneous combustion was established. Based on the multi-index fusion prediction model of coal spontaneous combustion, the multi-index fusion prediction method of coal spontaneous combustion at various stages was proposed.

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