Experimental study on characteristic parameters of coal spontaneous combustion

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Abstract

To investigate the spontaneous combustion of coal, a moderate scale experiment was carried out on the XK-III apparatus. Total 1500 kg coal was stored in the furnace with air supply. The coal undergone 39 days to reach 158 °C, at which the coal started to combustion. The temperature history of coal shows that the temperature rise was sped up after 30 days when the temperature is 60 °C. Before that, the coal was undergoing a slow oxidation process, and after that, the heating rate increased from 0.4 °C/h to 2.5 °C/h and the oxygen consumption increasing correspondingly. Furthermore, the production rate of CO and CO\textsubscript{2} increases rapidly. Therefore, the thermal runaway temperature is at 60 °C for the 1500 kg coal in a cylinder stockpile.

Keywords: Coal; Spontaneous combustion; Oxygen consumption velocity; Gas production rate.

Nomenclature

| Symbol | Description |
|--------|-------------|
| $z_i$ | distance to the entrance (m) |
| $C_o$ | standard oxygen concentration (21%) |
| $C_1$ | oxygen concentration at maximum temperature |
| $C_{co}^1$ | concentration of CO at $z_1$ |
| $C_{co}^2$ | concentration of CO at $z_2$ |
| $C_{co}^3$ | concentration of CO\textsubscript{2} at $z_1$ |
| $C_{co}^4$ | concentration of CO\textsubscript{2} at $z_2$ |
| $S$ | work face area (m\textsuperscript{2}) |
| $Q$ | air supply capacity (m\textsuperscript{3}/s) |
| $V_{co}^0$ | production rate of CO |
| $V_{co}^2$ | production rate of CO\textsubscript{2} |
| $v_{o}^0(T)$ | oxygen consumption velocity under the standard oxygen concentration(mol/s cm\textsuperscript{3}) |

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1. Introduction

Spontaneous combustion of coal occurs frequently in many coal mines, there are around 56% coal mines facing the probability of spontaneous combustion in China [1], which may result in great economic losses and casualties. It is widely accepted that low temperature oxidation is the main reason leading to the spontaneous combustion, and it originates from the exothermic reaction of coal and oxygen. Oxidation rate of coal at low temperature is a critical parameter for forecasting spontaneous combustion and self-heating, which is caused by exothermic chemical reactions between the coal and the oxygen, and the exothermic oxidation reaction is quite slow at the atmospheric temperature, and the reaction rate can be described by the Arrhenius law. The temperature rise will lead to increase of the reaction rate in return. If the heat generated is absorbed or dissipated by the surrounding environment, then spontaneous combustion would not occur, otherwise, if the heat generated is not removed to the exterior in time, then spontaneous combustion might occur [2]. Many technical methods on measuring the characteristic parameters of spontaneous combustion of coal have been carried out, which include differential thermal analysis (DTA) [2], adiabatic method [3, 4], thermal analysis [5] and so on. Stott et al. [6] first designed an experiment apparatus with length of 5 m and diameter of 0.6 m. Cliff et al [7] designed an experimental apparatus with capacity of 15 tons coal in Australia. Deng et al. [8] built a low temperature coal spontaneous combustion experimental apparatus, which could closely simulate the process of spontaneous combustion of coal in underground. It is difficult to find out the details of spontaneous combustion process due to its complexity [4]. Once spontaneous combustion happens in stored coal, the task of extinguishing the fire can be very difficult because of the amount of coal involved, and then it is difficult to forecast where and when self-heating will occur, because oxidation at low temperature is not obviously marked [1]. Therefore, measurement on characteristic parameters of spontaneous combustion of coal becomes even more important. In this work, the main purpose is to simulate the whole process of coal spontaneous combustion and analyse the characteristic parameters of coal spontaneous combustion.

2. Experimental

The occurrence and development of spontaneous combustion of coal are complicated physical and chemical processes. A coal spontaneous combustion experimental apparatus, named as XK-III [9, 10], was designed to simulate the whole process of spontaneous combustion. It includes furnace body, gas pipe and control measurement part (as shown in Fig. 1). The furnace body is a column with height of 175 cm, inner diameter of 120 cm, which can store 1575 kg coal sample in maximum. There are two circular openings with diameter of 10-20 cm at the bottom and top of the furnace body, respectively. The furnace wall includes insulating layer and temperature controllable water layer, and many thermocouples are placed in the furnace body. Air is supplied by air compressor, it enters humidity controller box and preheating water layer, and then it flows through the coal sample from the bottom and exhausts from the top. Some gas samples are extracted at the measuring point and analyzed with chromatographic analyzer. Temperature measurement, environmental temperature control and humidity control are managed by automatic control system.

![Fig. 1. Schematic diagram of XK-III coal spontaneous combustion experimental apparatus.](image-url)
The coal sample was obtained from Xieqiao Coal Mine in Anhui Province, China. Total 1500 kg coal sample was used in the experiment. It was milled and filled into furnace body, and then temperature control system was started and the air at a certain flow rate was supplied into the furnace body. The temperature difference between water layer and coal was adjusted to 1 °C. It was detected by the temperature control system and gas content was achieved by analyzing gas samples extracted at the measuring point with chromatographic analyzer. The coal sample was classified by different particle diameters: 0-0.9 mm, 0.9-3 mm, 3-5 mm, 5-7 mm, and more than 7 mm. The particle size fractions of the coal sample are given in Table 1, and other experimental conditions are shown in Table 2.

Table 1. Particle size fractions of the coal sample

| Particle Size (mm) | >7  | 5-7 | 3-5  | 0.9-3 | <0.9  |
|-------------------|-----|-----|------|-------|-------|
| Mass fraction (%) | 26.89 | 7.85 | 12.78 | 22.25 | 30.23 |

Table 2. Experimental conditions of spontaneous combustion of coal

| Parameters | Mean particle size (mm) | Height of samples (cm) | Mass (kg) | Volume of sample (cm³) | Density of lump coal (g/cm³) | Bulk density (g/cm³) | Porosity | Air supply capacity (m³/h) | Initial temperature (°C) |
|------------|-------------------------|------------------------|-----------|------------------------|-----------------------------|---------------------|----------|---------------------------|-------------------------|
| Sample     | 3.729                   | 150                    | 1500      | 1,695,600              | 1.40                        | 0.886               | 0.3528   | 0.15-0.3                  | 25.1                    |

3. Results and discussion

The experiment lasted for 39 days. Finally, the maximum temperature achieved 158 °C. Therefore, coal spontaneous combustion period was assumed to be 39 days. Fig. 2 shows that the temperature of coal increased slowly during the initial stage of experiment, and then the temperature of coal was sped up when the maximal temperature of coal reached 60 °C. However, when the maximum temperature have reached 110 °C, the temperature of coal increased rapidly, and then the temperature of coal presented the tendency of vertical line ascending when the maximal temperature of coal have reached 150 °C.

![Fig. 2. Maximum temperature as a function of time.](image1)

![Fig. 3. Heating rate as a function of time.](image2)

Heating rate of coal increases gradually with the rise of coal temperature, because the spontaneous combustion of coal is a long and slow process. The temperature of coal needs to take a long time to achieve a certain value and increase at an accelerated rate. Fig. 3 also shows that heating rate changes little when the time is less than 20 days, and it increases gradually when the time is above 20 days. However, it increases rapidly when the time exceeds 30 days, since when the heating rate is increased from 0.4 °C/h to 2.5 °C/h.

Figure 4 shows that heat liberation intensity increases gradually with increasing temperature of coal, it changes a little when the temperature of coal is less than 60 °C. However, heat liberation intensity increases rapidly when the temperature of coal is more than 60 °C.

It is thought that the oxygen consumption velocity is directly proportion to the oxygen concentration, Fig. 5 shows that
oxygen consumption velocity increases gradually with the rise of coal temperature, it increases slowly when the temperature of coal is less than 60 °C. However, oxygen consumption velocity increases rapidly when the temperature of coal is more than 60 °C. That is because oxygen consumption velocity is determined by the coal sample’s oxygen-adsorption velocity and recombination velocity at the lower temperature stage, and it is determined by the air supply velocity at the higher temperature stage.

Fig. 4. Heat liberation intensity as a function of temperature of coal. Fig. 5. Oxygen consumption velocity as a function of temperature of coal.

The heat released from the coal during the process of spontaneous combustion leads to the increase of coal temperature, and some gases will be released if the temperature reaches a certain value. The gases are called index gases and that can reflect the state of spontaneous combustion, where, CO and paraffin are the main gases for predicting the state of spontaneous combustion. Therefore, the progress of spontaneous combustion can be mastered and forecasted by analyzing the composition and content of the gases, which will be helpful for extinguishing the fire in the early stage [11]. The production rate of CO and CO₂ were mainly considered in this paper, and the production rate of CO was calculated as follows [9]:

\[
V_{co}^0(T) = \frac{V_{0z}^0(T) \cdot (C_{z_2}^{2} - C_{z_1}^{1})}{C_1 \cdot [1 - e^{\frac{Qs}{Qs_0}}]}
\]

where, \(V_{co}^0\) is the production rate of CO, \(z_1\) and \(z_2\) are the distance to the entrance, \(C_{z_1}^{1}\) and \(C_{z_2}^{2}\) are the concentration of CO at \(z_1\) and \(z_2\), respectively. \(V_{0z}^0(T)\) is the oxygen consumption rate under the standard oxygen concentration, \(C_1\) is the oxygen concentration at maximum temperature, \(s\) is the area of air supply, \(Q\) is the air supply capacity, \(Qs_0\) is the standard oxygen concentration.

Figure 6 shows that the production rate of CO increases gradually with temperature of coal increasing. It increase slowly when the temperature of coal is less than 60 °C, and the concentration of CO is almost in a fixed value when the temperature is below 50 °C. However, it increases rapidly when the coal temperature exceeds 60 °C. Therefore, when the production rate of CO achieves a certain level, the spontaneous combustion may occur. Some countermeasures can be taken to prevent the further development of coal spontaneous combustion.

In the similar way, the production rate of CO₂ was calculated as follows [9]:

\[
V_{co2}^0(T) = \frac{V_{0z}^0(T) \cdot (C_{z_2}^{2} - C_{z_1}^{1})}{C_1 \cdot [1 - e^{\frac{Qs}{Qs_0}}]}
\]

Figure 7 shows that the production rate of CO₂ increases along with the rise of coal temperature, and it increased slowly when the temperature of coal is less than 60 °C. However, production rate of CO₂ increases rapidly when the temperature is higher than 60 °C.
In the above experiment, when the temperature of coal sample reached 60 °C, the oxidation rate was accelerated. This process is accompanied with temperature, oxygen consumption velocity, CO and CO₂ production rate increasing sharply. Therefore, this temperature of 60 °C is the thermal runaway temperature of coal stockpile, and before it, the coal was undergoing low temperature oxidation slowly. Self-heating oxidation temperature (SHOT) of coal was proposed by Wang et al. [12] to evaluate the hazard degree of coal stockpile. The SHOT was calculated from Frank-Kamenetskii model with the data from micro-calorimeter experiments. For the results from the C80 experiments, the SHOTs based on the three experiments were calculated as 60 °C, 90 °C, and 68 °C, respectively [12]. These two kinds of methods can predict the similar results, and then it is concluded that 60 °C is the thermal runaway temperature for the 1500 kg coal in a cylinder stockpile.

4. Conclusions

The process of spontaneous combustion of coal can be successfully simulated by the XK-III coal spontaneous combustion experimental apparatus, and characteristic parameters of spontaneous combustion of coal were obtained based on some suitable hypothesis. The spontaneous combustion of coal occurred at 39 days in the experiment. The temperature history shows that the temperature rise was speeded up after 30 days. Concomitantly, the heating rate increased from 0.4 °C/h to 2.5 °C/h and the oxygen consumption increasing correspondingly. When the temperature exceeded 60 °C, both the production rate of CO and CO₂ increased rapidly. It is very important to analyze these characteristic parameters for early forecast of spontaneous combustion of coal. However, the experimental period is so long, and experimental conditions are not easy to control, so numerical simulation method should be established to make up for the deficiency in order to achieve correct results.

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