

# STUDY ON THE OXIDATION AND HEATING CHARACTERISTICS OF RESIDUAL COAL IN GOAFS UNDER DIFFERENT AIR-LEAKAGE CONDITIONS

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*The spontaneous combustion of broken coal is one of the main causes for mine safety accidents in goafs. To determine the effect of different air-leakage conditions on the spontaneous combustion of leftover coal, the air-leakage passage of the goaf was designed based on the principle of Sudoku grid in an inflammable coal seam. The temperature rise during the auto-ignition oxidation of coal was studied using a self-built experimental platform. By changing the air flow rate, the laws of the change in the oxygen consumption rate and the heat-release intensity with the coal temperature were analyzed. Results show that the oxygen consumption rate had three obvious peaks at 48°C, 75°C and 105°C, respectively. Above 80°C, spontaneous combustion of the experimental coal samples began. The exothermic intensity increased exponentially with the rise of temperature. Furthermore, an exponential relationship was observed between the air supply at the working face and the spontaneous combustion of broken coal in the goaf. In addition, the increase in air supply in the fully-mechanized mining face increased the width of the oxidation zone.*

Key words: goaf; air-leakage conditions; oxidation characteristics

## 1 Introduction

Spontaneous combustion is one of the five major disasters in the goaf of coal mines. It has always been a key focus in the field of mine safety [1-3]. Air leakage is the most direct cause of spontaneous combustion of coal in the goaf. As the goaf is semi-open and dynamically changes with the advancement of the working face, the air-leakage channel is constantly changing. Existing research results on the spontaneous combustion of coal and its oxidation characteristics cannot be used to explain the correlation between spontaneous combustion and oxidation temperature rise of broken coal with working face advancement in the goaf, and nor can they be used to prevent and control the catastrophes caused by the air-leakage flow field in the dynamic goaf. Therefore, it is necessary to conduct research on the oxidation and temperature-rise characteristics of the leftover coal in the goaf to provide a basis for the prediction and control of the spontaneous combustion of coal in the goaf.

Many previous studies have explored the spontaneous combustion of coal in the goaf. A spontaneous coal-combustion event at the Wangtaipu Coal Mine was analyzed [4] and the occurrence

conditions, mechanisms, and risk of spontaneous combustion were analyzed in a closed goaf. The influence of preheating with different oxygen concentrations on the spontaneous combustion behavior of secondary coal was investigated in [5]. During the secondary oxidation of coal, preheating at 80°C promoted the physical adsorption of oxygen at low temperatures; however, it reduced the oxidation at high temperatures. The intersection point temperature (CPT) and isothermal oxidation characteristics of coal were analyzed [6], and it is reported that the upgraded low-grade coal was less sensitive to low-temperature oxidation and spontaneous combustion. The Particle Flow Code in 3 Dimensions (PFC3D) framework was used to establish a numerical model based on short-distance coal seam mining, and it was found that the air-leakage passage scope rapidly expanded with the roof rupture of the lower coal seam in the goaf [7]. With the periodic breakage of the roof, the air-leakage channel kept moving forward. A model of gas leakage and diffusion was established in the goaf of the third seam top coal caving mining of the Jishan Coal Mine [8]. An experimental study [9] found that coal samples would undergo an exothermic oxidation reaction and support the continuous expansion of the fire area in high temperature, oxygen-poor environment. It was also pointed out [10] that the specific surface area of coal sample had a direct effect on the coal oxidation rate, when the coal sample particle size was greater than 0.1 mm. Air-leakage channel, porosity and oxygen leakage expansion law of the goaf roof in the mined-out area near a thin belt was investigated through numerical model [11]. It was found that the air-leakage channel was constantly moving forward, prompting the lower coal seam to leak oxygen into the upper coal seam goaf. The spontaneous combustion of the remaining coal was intensified in the upper coal seam goaf. A total of 3308 working faces at the Liangbaosi Coal Mine in China were examined [12], and PFC3D was used to simulate the overburden collapse. It was found that the central and nearby goafs had relatively large porosity, and that, as the height of the mined-out area increased, the porosity of the two cross-shaped wellheads was first larger than that of the middle part, and then smaller. The main air leakage occurred in the range of 0-10 m along the slope of the working surface. The concept of pressure gradient matrix and related calculation methods to analyze potential air-leakage paths was proposed [13]. Electron spin resonance spectroscopy was used to measure directly the changing laws of different types and particle sizes of coal, and it was proposed that the fracture process was the key factor to generate and initiate free radical reactions [14]. One-dimensional mine ventilation network (MVN) was coupled with a 2D/3D gob flow field (GFF), and MVN analysis was used to evaluate the boundary pressure of the GFF simulation [15]. FTM fed back the GFF result to the coupling network.

It can be seen from the above literature survey that the relationship between air-leakage conditions and coal oxidation characteristics has so far been discussed considering only a single air-leakage channel with the air leakage assumed to be uniform. In other words, the possibility of multiple air-leakage channels was ignored. Such an approach cannot obviously address the characteristics of several concurrent and nonuniform air-leakage channels in the goaf. Based on this observation, the influence of different air-leakage conditions on the spontaneous coal combustion in the goaf of combustible coal seams in deep mines needs to be studied urgently. To that end, a coal spontaneous combustion test system with a nine-square grid was built to study multi-channel air leakage. Three types of uneven air-leakage channels are designed. The experiments examined coal spontaneous combustion temperature increase and oxidation. The heating and oxidation process and law of coal left are discussed for different air-leakage conditions in the goaf. The influence of different air-leakage conditions on the spontaneous combustion characteristics of coal in the goaf is examined.

## 2 Experimental system

### 2.1 Preparation of experimental coal samples

The experimental coal sample was taken from mine No. 1 of the Yungaishan Coal Mine (“Yunmei No. 1 Mine”) belonging to the Yongjin Energy Company, Henan Province, China. Yunmei No. 1 Mine is located in Foshan Village, Mojie Town, Yuzhou City, Xuchang City, Henan Province. The mine was evaluated as a high gas mine.

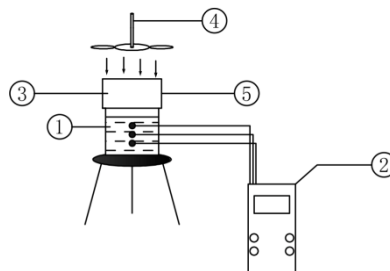
The coal sample was pre-processed and screened using a mesh screen prior to the experiment. The parameters of the coal sample are shown in Table 1.

**Table 1 Parameters of the experimental coal sample**

Parameter	Value
Average particle size, [mm]	3.629
Coal pile height, [cm]	80
Coal pile bottom area, [cm <sup>2</sup> ]	225
Void ratio [-]	0.3528
Air supply flow, [m <sup>3</sup> /s]	$95 \times 10^{-6}$ – $300 \times 10^{-6}$
Initial temperature, [°C]	21
Lump coal density, [gcm <sup>-3</sup> ]	1.43
Bulk coal density, [gcm <sup>-3</sup> ]	0.948
Specific heat, [Jm <sup>-3</sup> °C <sup>-1</sup> ]	$5.12 \times 10^5$
Thermal conductivity, [Wm <sup>-1</sup> °C <sup>-1</sup> ]	1.72

### 2.2 Parameters of experimental system components

The components and parameters of the coal spontaneous combustion experimental system were 15 cm × 15 cm × 10 cm, three-leg combustion platform ( $h = 15$  cm), asbestos net ( $d = 20$  cm), closed cover with micro-holes ( $16 \times 16 \times 5$ ), three thermocouples, a CO gas concentration detector, and an air supply device. The schematic diagram of the experimental system is shown in Fig. 1.

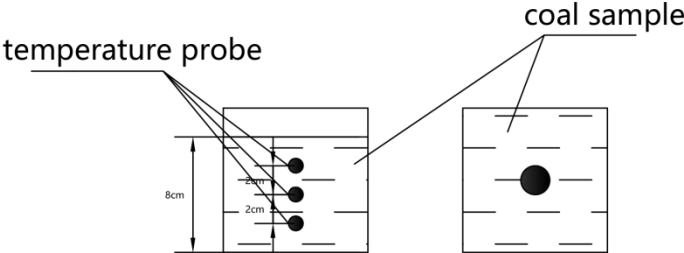


**Fig. 1 The experimental system in the present study**

### 2.3 Experimental process

(1) The test coal sample was formed into a long cuboid (15 cm × 15 cm × 8 cm). Temperature measuring probes were set every 2 cm along the neutral surface inside the cuboid coal sample. The probes were denoted as A, B, and C from the bottom to the top, and were evenly distributed in the coal

sample to measure accurately the temperature change of the coal sample during the experiment. The locations of the temperature probes are shown in Fig. 2.



**Fig. 2 Temperature measurement points**

(2) The spontaneous coal-combustion test bench was placed in the goaf under a sealing cover with micro-holes. The number of micro-holes was set gradually in accordance with the number of grids in the nine-square grid. Each small grid area was provided with three micro-holes for air supply.

(3) The coal sample was indirectly heated by a thermoelectric rod. At the same time, the ventilator was turned on to supply air to the microspores. Three types of air leakage were simulated. The changes in the internal temperature and CO concentration were measured.

(4) When the temperature was raised to the spontaneous ignition point of 80°C at Point A at the lower part of the coal sample, the external heating was stopped.

(5) The changes in such parameters as temperature, CO concentration, and O<sub>2</sub> concentration of the experimental coal sample were recorded every 1 s for 1 h. There were 3600 data for each parameter in the experiment. When processing the data, one was selected every 100 s. There were a total of 36 data.

**3 Design of air-leakage channel based on the principle of nine-square grid**

The above experimental process shows that the size of the air leakage must be changed by gradually changing the micro pore distribution in the cover. The micropore airtight cover was divided into nine grids, as shown in Fig. 3. In the experiment, three areas were selected to simulate different air-leakage channels: Area 1 comprised grids 4-5-6, Area 2 grids 1-3-5-7-9, and Area 3 grids 1-2-3-4-5-6-7-8-9, respectively. An anemometer was used to measure the average wind speed of each cell, and then the average wind speed of each area was calculated, as shown in Table 2.

1	2	3
4	5	6
7	8	9

**Fig. 3 Grid of micro-hole distribution sin airtight cover**

**Table2 Air-leakage passage wind velocity of each cross-section**

Experiment No.							Average wind velocity (of experiments)
		1	2	3	4	5	
1		3.2	3.4	3.4	3.5	3.3	3.36
2		3.4	3.6	3.5	3.4	3.5	3.48
3		3.6	3.6	3.3	3.7	3.5	3.24
4	Grid No.	3.4	3.4	3.5	3.5	3.4	3.44
5		4.1	4.3	4.5	4.5	4.5	4.38
6		3.3	3.6	3.5	3.4	3.5	3.46
7		3.4	3.3	3.2	3.3	3.4	3.32
8		3.6	3.3	3.3	3.2	3.5	3.44
9		3.5	3.2	3.4	3.3	3.2	3.32
Average wind velocity (of grids)		3.5	3.5	3.5	3.5	3.5	3.5

The diameter of micro pore in the airtight cover was 2 mm, and there were three micro pores in each cell on average. The air-leakage area,  $S$  (m<sup>2</sup>), of each cell can be calculated follows:

$$S = 3.14 \times R^2 \times 3 = 9.42 \times 10^{-6} \quad (1)$$

The simulated air leakage,  $Q$  (m<sup>3</sup>/s), can be expressed as follows:

$$Q = vS \quad (2)$$

During the experiment, the amount of air leakage was changed by opening different numbers of micro pores in the airtight cover. The amount of air leakage is shown in Table 3.

**Table 3 Determination of the air leakage rate**

Number	$v$ [m/s]	$Q$ [m <sup>3</sup> /s]
Area1	3.46	$97.78 \times 10^{-6}$ (small)
Area 2	3.52	$165.80 \times 10^{-6}$ (medium)
Area 3	3.49	$295.88 \times 10^{-6}$ (large)

## 4 Results and discussion

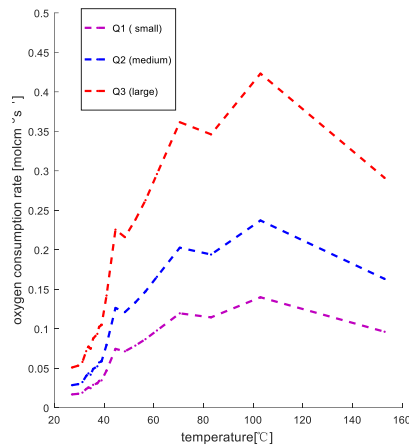
To study the characteristics of spontaneous coal combustion with changing air leakage, it is necessary to start with oxygen consumption rate and heat-release intensity [16]. These results are discussed below.

### 4.1 Analysis of oxygen consumption rate

The current methods of calculating the oxygen consumption rate differ depending on whether porosity. One was the formula derived by Liu [17], and the other was the formula derived by Xu [18]. This paper used Eq. (3) to calculate  $V(T)$ . It can be expressed as [17].]:

$$V(T) = \frac{Q(C_1 - C_2)}{sLn} \quad (3)$$

The experimental data was substituted into Eq. (3). The relationship between the coal sample temperature and the oxygen consumption rate was obtained for different air-leakage rates, as is shown in Fig. 4.



**Fig. 4 Change in oxygen consumption rate for different air-leakage rates**

Fig. 4 shows that there was a close correlation between oxygen consumption rate and air leakage. There are three obvious peaks. The first peak is around 48°C. In the initial stage of coal oxidation in the experimental chamber, the heat generated was less than the heat released to the outside. The temperature of the second peak was about 75°C. At this time, the experimental coal sample entered the second stage of oxidation - the spontaneous combustion stage. A change in oxygen consumption rate can clearly be seen. With the influence of the air leakage in the goaf, the experimental coal sample did not directly enter the third-stage combustion. Instead, the oxygen consumption rate showed a decline, because the incoming air flow reduced the temperature in the experimental chamber. While the oxidation heat release of coal dominated, the third peak occurred at a temperature of about 105°C. The experimental coal sample began to burn, and as the coal sample was being consumed, the heat release to the outside environment was dominant. As a result, the oxygen consumption rate declined sharply.

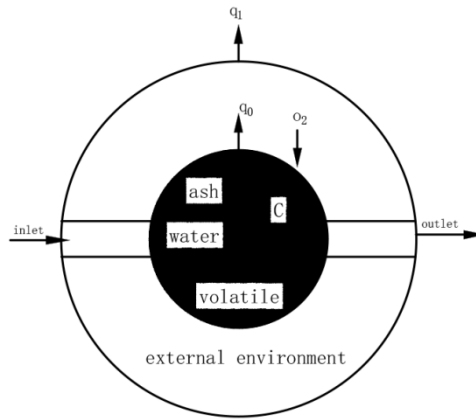
With a small air flow rate, the change in the peak value was gentler, and the temperatures were the lowest at the three peaks. Compared to other air flow rates, the temperature of the peak changed only a little. It was found that the change in the air flow had an impact on the peak oxygen consumption rate, but its impact on volatility was not obvious. With different air flow rates, the peak values of three oxygen consumption rates were all closely related to the air flow rate. For larger air flow rates, the peak oxygen consumption rates were higher and the peak differences were larger. Because the air flow velocity was large, the oxygen supply was sufficient, and this was conducive to the oxidation of the experimental coal samples.

For a single air-leakage channel, it is believed [17] that different air flows had little effect on the growth trend of the standard oxygen consumption rate. Also, the growth trend was assumed to be exponential. With multi-channel air leakage, the relationship was a step increase between the oxygen consumption rate and the air leakage. For larger air flow rates, the peak oxygen consumption rates were higher and the peak differences larger. With small air leakage, the change of air flow had no obvious influence on the fluctuation of oxygen consumption peak rate.

## 4.2 Heat-release intensity

For coal at low temperatures, there are two methods to calculate the exothermic strength,  $q(T)$ , namely, the heat balance method,  $q_0(T)$ , and the bond energy estimation method,  $(q_{min}(T), q_{max}(T))$ . The heat balance calculation method can be used to calculate the heat-release intensity. The bond energy estimation method only serves as a verification result[19]. Therefore, this paper used the heat balance method to derive the heat-release intensity,  $q_0(T)$ , of coal oxidation at low temperature.

Assuming that  $T_{air}$  that flows through the coal pile in this experiment cavity is equal to  $T_{coal}$ , the air flew along the longitudinal axis. The only heat exchange only considered was coal oxidation heat release, cavity wall conduction heat dissipation and the convection heat dissipation of the air flow in the cavity during the coal oxidation process, and other heat exchanges were ignored. The heat field exchange in the experimental chamber is shown in Fig. 5.



**Fig. 5 Heat exchange diagram of experimental chamber**

At the center of the experimental cavity, the heat balance equation can be expressed as follows [19]:

$$q(T) = \rho_e c_e \frac{\partial T}{\partial t} + \bar{Q} \rho_g c_g \frac{\partial T}{\partial t} - \lambda_e \left[ \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} \right] \quad (4)$$

$$\frac{1}{\lambda_e} = \frac{1}{\lambda_g} + (1-n) \frac{1}{\lambda_m} \quad (5)$$

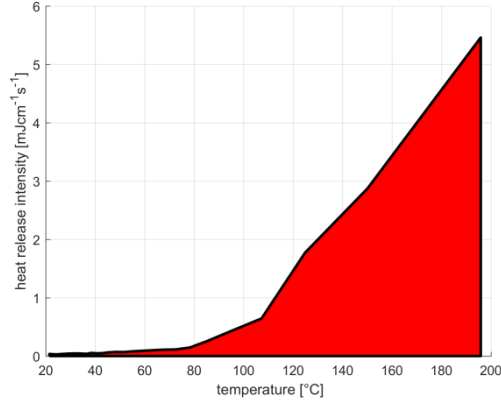
$$c_e = n c_g + (1-n) c_m \quad (6)$$

$$\rho_e = n \rho_g + (1-n) \rho_m \quad (7)$$

During the low-temperature oxidation stage, the oxidation exothermic intensity of coal,  $q(T)$ , is proportional to the oxygen mass concentration,  $C$  [19]. The relationship between temperature and  $q_0(T)$  is as follows:

$$q_0(T) = (C_0 / C_1) q(T) \quad (8)$$

and shown in Fig. 6.



**Fig. 6 Variation of exothermic intensity of experimental coal sample**

From Fig. 6, when the temperature reaches about 80°C, the exothermic intensity calculated by the heat balance method exhibits an exponential increase as the the temperature rises. Below 80°C, the heat release of coal samples was very limited and was hardly changing. In that stage the accumulated heat and the released heat competed with each other.

#### 4.3 Relationship analysis between air supply and air leakage

The amount of air leakage is depended on the amount of air supplied to the working face in the goaf. When other conditions remain unchanged, the amount of air supplied becomes larger at the working face, and the pressure drop increases. It is thus obvious that the amount of air leakage must be increased. The relationship between the working face pressure drop,  $\Delta h$ , and air supply can be expressed as follows [12]:

$$\Delta h = R(Q_{in} + Q_{out})^2 / 4 \quad (9)$$

The actual air leakage at the working face,  $\Delta Q$ , can be expressed as follows:

$$\Delta Q = Q_{in} - Q_{out} \quad (10)$$

The air leakage per unit area in the goaf,  $\Delta Q_{leak}$ , can be expressed as follows:

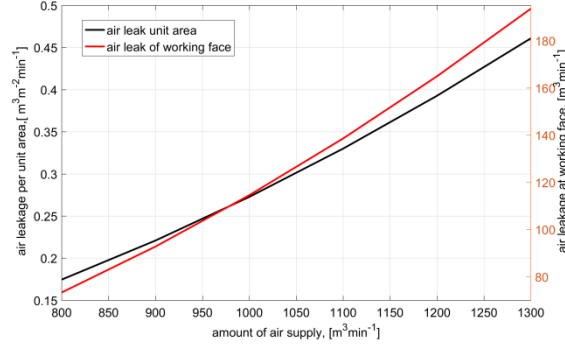
$$\Delta Q_{leak} = \frac{4(Q_{in} - Q_{out})}{LH(Q_{in} + Q_{out})^2} Q^2 \quad (11)$$

According to the actual measurement at the fully mechanized coal face,  $Q_{in}=915$ ,  $Q_{out}=828$ ,  $L = 120$ ,  $H = 3.5$ ,  $\Delta h = 24.5$ . The air-leakage rates at the fully mechanized coal face are shown in Table 4. The relationship between the air-leakage rate and the air supply rate is also shown in Fig. 7.

**Table 4 Relationship between air supply and air leakage**

Variables	Air supply					
	800	900	1000	1100	1200	1300
$\Delta Q_{leak}$	0.1745	0.2209	0.2727	0.33	0.3927	0.4609
$\Delta Q$	73.31	92.78	114.55	138.60	164.95	193.59





**Fig. 7 Relationship between air leakage and air supply**

From Fig. 7, the air leakage per unit area of the goaf and the air leakage at the fully mechanized mining face are approximately in a linear relationship with the air supply at the working face. The greater the air supply at the working face, the greater the air leakage per unit area of the goaf and the air leakage at the fully mechanized mining face were. This is because increasing air supply to the working face improved the pressure drop at both ends of the working face. If no measures are taken in the air-leakage channel, the air leakage would be increased in the goaf.

#### 4.4 Relationship between air supply to working face and width of oxidation zone

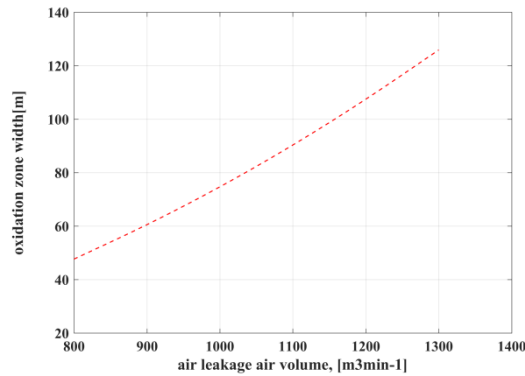
The oxygen consumption rate was  $3.74 \times 10^{-2} \text{ mol} \cdot \text{m}^{-3} \cdot \text{min}^{-1}$  when the oxygen concentration was 20.9%. It was assumed that there was no temperature difference in the goaf. The width of the oxidation zone can be expressed as follows [13]:

$$w = \int_{[O_2]_{\min}}^{[O_2]_1} \Delta Q_{\text{leak}} \frac{d[O_2]}{v} \quad (11)$$

Combining Eqs. (10) and (11), the relationship between the width of the oxidation zone and the air volume at the fully mechanized caving face can be obtained as

$$w = \frac{1000}{22.4} Q^2 \frac{4(Q_{in} - Q_{out})[O_2]_0}{LH(Q_{in} + Q_{out})^2 v_0} \ln \frac{[O_2]_1}{[O_2]_{\min}} \quad (12)$$

The relationship between the air supply and the width of the oxidation zone is shown in Fig. 8.



**Fig. 8 Relationship between air supply and oxidation zone width**

As Fig. 8 shows, for a fully mechanized coal mining face of the combustible coal seam, the air leakage in the goaf and the air leakage on the fully-machanized mining face are linearly correlated to

the air supply to the working face. The increase of air supply in fully mechanized mining face would increase the width of oxidation zone. The air supply reached a certain value, and the air leakage meet the coal spontaneous combustion requirements. The thickness of the broken coal at the fully mechanized mining face was thicker in the goaf, if the top coal mining technology was selected. This can reduce the advancing speed of the working face. During the minimum coal spontaneous combustion period, when the advancing distance of the working face was greater than the width of the oxidation zone in the goaf, the coal body could not combust spontaneously. On the contrary, it was more likely to cause spontaneous combustion of into in the oxidation zone.

For the fully mechanized top coal caving face of the coal mine studied in this example, the air supply was  $915 \text{ m}^3 \text{ min}^{-1}$ , and the oxidation zone width was calculated to be 62.36 m. The shortest fire period was measured to be 35 days, while the average advancement of the face was  $2 \text{ m} \cdot \text{d}^{-1}$ . The advancing distance was 70 m in the shortest spontaneous ignition period. The width of the oxidation zone was smaller than the advancing distance in the shortest spontaneous ignition period. Obviously, the risk of spontaneous combustion was relatively high in the goaf. If the air supply volume of the mining face was adjusted to  $100 \text{ m}^3 \text{ min}^{-1}$ , the width of the oxidation zone was calculated to be 74.49 m. The width of the oxidation zone was greater than the advancing distance during the shortest spontaneous combustion period. Overall, the risk of spontaneous combustion was relatively low in the goaf.

## 5 Conclusions

(1) With the influence of multiple air-leakage channels, if the void ratio of the coal sample was considered, the oxygen consumption rate exhibited three obvious peaks, and the peak values increased with the increasing air-leakage. Compared to large air flow, in small air flow the changes of the peak values were relatively gentle, and three peaks of temperature were the lowest. The greater the air flow, the larger the peak oxygen consumption rate and the greater the peak difference.

(2) Below  $80^\circ\text{C}$ , the difference was not large between the heat release and heat dissipation of the coal sample, and the heat-release intensity hardly changed. Above  $80^\circ\text{C}$ , the heat generated by the experimental coal sample began to dominate, and became far greater than the heat exchange to the outside. The relationship was exponential.

(3) The air-leakage rate per unit area of the goaf and the air-leakage rate at the fully mechanized mining face exhibited an approximately linear change with the air supply rate at the working face. The width of the oxidation zone had an exponential relationship with the air supply in the goaf. Specifically, for fully mechanized caving mining the remaining coal, the advancement of the working face was slower than the safe speed. When the air-leakage channels were increased, this could easily cause spontaneous combustion of coal in the goaf.

(4) By analyzing the relationship between different air-leakage conditions and the spontaneous temperature-rise characteristics of floating coal in the goaf, combined with the data measured and obtained in the goaf and experimental measurements, the risk of spontaneous combustion of the coal seam in the goaf could be predicted more accurately. This could guide the formulation of on-site fire-fighting technical measures.

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## Nomenclature

- $C_1$  — oxygen concentration at inlet, [=20.9%]  
 $C_2$  — oxygen concentration at outlet, [%]  
 $c_m, c_g$  — experimental specific heat capacity of coal sample and air, [ $\text{Jg}^{-1}\text{C}^{-1}$ ]  
 $\Delta h$  — working face pressure drop, [Pa]  
 $L, H$  — length and mining height of fully mechanized mining face, [m]  
 $\lambda_m, \lambda_g$  — thermal conductivity of experimental coal sample and air, [ $\text{Jcm}^{-1}\text{s}^{-1}\text{C}^{-1}$ ]  
 $n$  — void ratio of experimental coal sample, [=0.45]  
 $[O_2]_0$  — the oxygen concentration when the oxygen consumption rate is  $v_0$  [=20.9%]  
 $[O_2]_1$  — oxygen concentration upper limit, [=20.8%]  
 $[O_2]_{min}$  — oxygen concentration lower limit, [=6.96%]  
 $q(T)$  — heat-release intensity at temperature  $T$ , [ $\text{Jcm}^{-1}\text{s}^{-1}$ ]  
 $q_0(T)$  — oxidation exothermic intensity at temperature  $T$ , [ $\text{Jcm}^{-1}\text{s}^{-1}$ ]  
 $Q$  — air leakage air volume, [ $\text{m}^3\text{min}^{-1}$ ]  
 $Q_{in}, Q_{out}$  — intake and return air volume of mining face, [ $\text{m}^3\text{min}^{-1}$ ]  
 $\Delta Q_{leak}$  — air leakage per unit area, [ $\text{m}^3\text{m}^{-2}\text{min}^{-1}$ ]  
 $r$  — transverse length of experimental cavity, [m]  
 $R$  — radius of micro pores, [m]  
 $\rho_g, \rho_m$  — equivalent density of air and experimental coal sample, [ $\text{gcm}^{-3}$ ]  
 $s$  — cross-sectional area of experimental goaf, [ $\text{m}^2$ ]  
 $S$  — air-leakage area of cell, [ $\text{m}^2$ ]  
 $T$  — time, [s]  
 $v$  — average wind speed through section, [ $\text{ms}^{-1}$ ]  
 $V(T)$  — oxygen consumption rate, [ $\text{molcm}^{-3}\text{s}^{-1}$ ]  
 $z$  — length of experimental cavity, [cm].

## References

- [1] Man, T.L. and Wang W., Numerical simulation of three-dimensional air leakage flow field in goaf based on CFD(in Chinese), *Coal engineering*, 51(2019)9, pp. 142-146  
 [2] Choi, H.Y., *et al.*, Comparison of spontaneous combustion susceptibility of coal dried by different processes from low-rank coal, *korean journal of chemical engineering*, 31(2014), 12, pp. 2151-2156  
 [3] Deng, J., *et al.*, Effects of pyrite on the spontaneous combustion of coal, *International Journal of Coal Science & Technology*, 2(2015)4, pp. 306-311  
 [4] Pan, R., *et al.*, The inducement of coal spontaneous combustion disaster and control technology in a wide range of coal mine closed area, *Environmental Earth Sciences*, 77(2018), pp. 374-381

- [5] Wang, K., *et al.*, Effects of pre-oxidation temperature on coal secondary spontaneous combustion, *Journal of Thermal Analysis and Calorimetry*, 138 (2019), pp. 1363-1370
- [6] Choi, H. K. *et al.*, Low Temperature Oxidation and Spontaneous Combustion Characteristics of Upgraded Low Rank Coal, *International Symposium on Coal Combustion*, 8(2013), pp. 75-79
- [7] Zhang, M., *et al.*, Numerical Analysis of Air Leakage Characteristics of Coal Seam Goaf Close to Thin Band, *Geotechnical and Geological Engineering*, 36(2018), pp. 3149-3158
- [8] Li, M., *et al.*, Analysis on air-leakage law of goaf in condition of ascending mining for top-coal caving, *Journal of Coal Science and Engineering (China)*, 15(2009), pp.81-84
- [9] Beamish, B. B., *et al.*, Spontaneous combustion propensity of New Zealand coals under adiabatic conditions, *International Journal of coal Geology*, 45(2001), pp. 217-224
- [10] Pan, R., *et al.*, Experimental study on the effects of chemical composite additive on the microscopic characteristics of spontaneous combustion coal, *Environmental Science and Pollution Research*, 27(2020), pp. 5606–5619.
- [11] Zhang, M.G., *et al.*, Numerical Analysis of Air Leakage Characteristics of Coal Seam Goaf Close to Thin Band, *Geotechnical and Geological Engineering*, 36(2018), pp. 3149-3158.
- [12] Deng, J., *et al.*, Thermal analysis of spontaneous combustion behavior of partially oxidized coal, *process safety and environmental protection*, 104(2016), pp. 218-24
- [13] Zhang, J., *et al.*, Analysis of mine's air leakage based on pressure gradient matrix between nodes, *Journal of Coal Science and Engineering (China)*, 14(2008), pp. 443-446
- [14] Li, Z., *et al.*, Free radical reaction characteristics of coal low-temperature oxidation and its inhibition method, *Environmental Science and Pollution Research*, 23(2016), pp. 23593–23605
- [15] Wen, H., *et al.*, Technique of measurement and test of coal spontaneous combustion characteristic and numerical analysis, *Journal of university of science and technology Beijing*, 23(2001), pp. 499-501
- [16] Jo, W., *et al.*, A comparison of spontaneous combustion susceptibility of coal according to its rank, *Korean Journal of Chemical Engineering*, 30(2013), pp. 1034-1038
- [17] Qin, Y.P., *et al.*, Study on the influence of air flow on spontaneous combustion characteristics of remnant coal (in Chinese), *Coal Mines Safety*, 45(2014)1, pp. 34-38
- [18] Xu, J.C., *et al.*, *Judgment Theory of Coal Spontaneous Combustion Hazardous Area*, Coal Industry Press, Beijing, 2001
- [19] Xu, J.C., *et al.*, Determination and calculation of low-temperature oxidation heat release intensity of loose coal (in Chinese), *Journal of China Coal Society*, 25(2000)4, pp.387-391