Experimental study on the spatial and temporal variations of temperature and indicator gases during coal spontaneous combustion

Junchao Chen, Lin Li, Deyi Jiang, Lei Zhou and Liang Wang

Abstract
Coal spontaneous combustion is one of the main potential hazards in the process of mining. To study the spatial and temporal variations of higher-temperature area and indicator gases, an adiabatic oxidation testing system was developed to simulate the whole process of coal spontaneous combustion. The experimental results show that the entire process of coal spontaneous combustion could be divided into three stages: slow-oxidation, accelerated-oxidation and combustion stages. In the slow-oxidation stage, the higher-temperature area shifted slowly from the bottom to the top and then stayed at the top until accelerated-oxidation stage was reached; CO and CO₂ concentration remained more or less constant as well as the oxygen concentration. In accelerated-oxidation stage, the higher-temperature area moved to the bottom rapidly and subsequently stayed approximately in the center of the coal; CO, CO₂ concentration and oxygen consumption increased sharply. In addition, the occurrence of higher-temperature area is accompanied by higher oxygen consumption. The obtained results show that higher air supply rate could shorten spontaneous combustion period and there exists a hyperbolic relationship between the temperature and time.

Keywords
Spontaneous combustion, indicator gas, oxygen concentration, temperature
Introduction

Coal is one of the main energy sources in the world (Ren et al., 2019; Zhang et al., 2018a). In China, coal fire is one of the main hazards in coal mines, most of which were caused by coal spontaneous combustion. This indicates that on one hand, a large amount of coal resources are wasted annually by coal fire; on the other hand, coal spontaneous combustion also influences the coal production greatly. So far, it is well-known that coal spontaneous combustion contains not only physical reactions but also chemical (coal-oxygen) reactions (Cheng et al., 2017; Fan et al., 2020a; Ge et al., 2019; Ren et al., 1999; Zhang et al., 2018b, 2020).

In the past decades, international and domestic academics have conducted extensive researches on coal spontaneous combustion aiming at exploring the mechanism of this phenomenon through experimental tests (Beamish et al., 2003; Benfell et al., 1997; Peng et al., 2020; Yang et al., 2018) and numerical simulations (Fan et al., 2020b; Jiang et al., 2008; Song et al., 2015). Obviously, in comparison with numerical simulations, the experimental tests are more realistic and suitable for in situ cases, which is primarily because many assumptions (contradictory with the fact) are directly simplified in numerical simulations. Therefore, more attention has been paid to the physical modeling of coal spontaneous combustion. At present, better understanding of this topic has been successfully achieved. These results show that coal spontaneous combustion is impacted by a couple of factors, primarily consisting of particle size, oxygen concentration, air supply rate and temperature. Temperature is the most significant influence factor on coal spontaneous combustion. The increase in coal temperature could result in the formation of indicator gases (such as CO, C2H4, CO2). Thus, to predict coal spontaneous combustion, it is necessary to analyze the precursors (e.g., indicator gases, temperature) which would occur during the combustion process. Zhou et al. (2010) analyzed the gas (CO, C2H4, CO2) generation laws at different oxygen concentration. Liu et al. (2013) put forward the energy migration theory of spontaneous combustion and obtained the empirical equation of the higher temperature area in the gob and of the minimum safety mining velocity. Wang et al. (2018) proved that the liberations of CO, H2, CO2 are positively related to the oxygen consumption. Luo et al. (2019) pointed out that the liberations of hydrocarbons (CO) first rise and then descend with the decrease in particle size. However, the above-mentioned experiments were on relatively small scales. Although these results could provide convincing explanations in some aspects, it is not completely suitable for the real coal mines on account that some parameters can not be directly detected (Yang et al., 2018).

Therefore, large-scale tests seem to be a better stepping-stone for exploring the true physics of coal spontaneous combustion. Zhou et al. (2009) employed a large-scale device to investigate the liberation of indicator gases. Deng et al. (2015) studied the variations of temperature and indicator gases with a 15 tons testing system. However, it is found that due to the limitation of the experimental device, the spatial and temporal variation of the higher-temperature area and indicator gases have not been fully understood. In fact, dynamic variation of high-temperature area reflects the development of the interaction of heat accumulation and migration, which is the basis of mechanism and significant for the prediction of coal spontaneous combustion. In this work, the aim is to simulate the whole process of spontaneous combustion using an adiabatic oxidation testing system, and to study the variations of higher-temperature area and indicator gases. The results from this work can provide an improved understanding of precursors which appears in the combustion process.
Testing sample and scheme

The coal sample was collected from Tashan mine, which is located in the city of Datong, Shanxi province, China. The coal was first crushed and then sieved out for the prescribed particle size. To avoid oxidation reaction and keep the coal sample as fresh as possible, it was wrapped with aluminium foil and then was put into the fridge. The corresponding parameters for the coal are listed in Table 1.

The 2 m adiabatic self-heating device was adopted for this issue as shown in Figure 1. Testing system mainly consists of the experimental furnace, temperature switcher, signal controller, computer system, gas compressor, etc. First the coal sample is placed in the furnace (the top thermocouple must be covered). Subsequently, the thermocouples are inserted into the coal through the holes on the furnace wall as shown in Figure 1. Gastightness is examined before testing. Finally, the test starts with the initial temperature

| Particle size (mm) | Mass (kg) | Height (cm) | Humidity (%) | Ash (%) | volatiles (%) | Calorific value (MJ/kg) | Porosity (%) |
|--------------------|-----------|-------------|--------------|---------|---------------|------------------------|-------------|
| 6.83               | 55.2      | 198.1       | 15.4         | 18.2    | 34.6          | 22.8                   | 0.4         |

Table 1. Coal parameters used in the experiment.

Figure 1. The testing system.
and preset air supply rate. During the test, the temperatures for two positions are monitored: one is at the center and the other is on the furnace wall at the corresponding height. To reduce the loss of the heat generated by oxidation reaction, both temperatures are always kept close to each other using a heater. The temperature was automatically recorded every 10 minutes and the maximum value in one day was chosen for analysis. The gas sample at different heights was collected through the holes on the furnace wall to analyze the gas composition and concentration with Odalog 6000 (Figure 2). 2 hours (fixed time) on each day were spent on monitoring the concentration of each indicator gas and the average was determined for analysis.

**Testing results**

*Spatial and temporal variation of higher-temperature area*

The important indicator that directly reflects the degree of coal spontaneous combustion is the temperature of the coal. As time went on, the temperatures of the coal at different heights continuously varied during coal spontaneous combustion. The variations of each monitored point in temperature are shown in Figure 3. The y-axis stands for the height of the furnace and eight monitored points are vertically distributed at 37 cm, 55 cm, 73 cm, 91 cm, 109 cm, 127 cm, 145 cm, 163 cm away from the air inlet (the bottom). The initial temperature of the coal was set to be 25°C.

Figure 3 shows that the temperature in different positions and the higher-temperature area were in the dynamic change. As can be seen from Figure 3, there was no significant difference in the temperature in the first day. However, from the second day, the temperature of each point increased at different heating rates and a relative higher-temperature area gradually appears. First the higher-temperature area came out at 109 cm (approximately in the center of the coal). At this moment, the heating rate of the coal is still slow. As time passed, in particular when the temperature exceeded 30°C, the higher-temperature area began to move towards the top. It shifted first at 127 cm and then moved rapidly at 163 cm (at this moment, the temperature of the upper coal increased more than the lower; the temperature at 163 cm has exceeded 40°C). It is interesting that the higher-temperature
area remained at 163 cm for a long time. Until the 68th day, it started to move towards 127 cm again and the temperature is beyond 80°C. Subsequently, the temperature at 127 cm increased rapidly and the coal began to burn severely.

In general, the oxygen consumption during coal spontaneous combustion are mainly attributed to the physical adsorption, chemical adsorption and chemical reaction. In the initial stage, the oxygen consumption of physical adsorption accounted for the largest proportion (Ma et al., 2006). However, the amount of released heat from physical adsorption was small. Therefore, the heat accumulated very slowly and there was no significant difference in the temperature of coal body. But as time went on, the higher-temperature area was firstly generated in the central area (approximately 109 cm). The main reason for this could be the preferable condition of heat storage in the central area. The bottom of the coal was more intensive due to the gravity (contact area with oxygen was relatively small) and was also greatly affected by air-leakage; the heat generated from the top of the coal was taken out from the outlet. The results indicate that oxidation reaction was not significant below 35°C. However, with the rise in temperature, activation energy required for oxidation reaction was decreased remarkably and meanwhile the number of reactive functional groups increased rapidly. Furthermore, this brought about the acceleration of coal oxidation reaction. Since the top of the coal was more loosen and has more contact areas with oxygen, the higher-temperature area then moved to the top and the corresponding temperature increased rapidly. But the coal did not immediately burn on account that the heat produced was transferred partially to the outlet with the airflow. As the test went on, the oxygen concentration at the top could not satisfy the requirement of higher oxidation reaction. Therefore, the higher-temperature area went down where the oxygen concentration is higher and stayed at 127 cm again. Soon the temperature at 127 cm increased sharply to the kindling point.

On another aspect, it is apparent that the heating rate of the upper coal is higher than the lower. As time passed, $R_{70}$ value (the average heating rate from 40°C to 70°C) and the heating intensity were enhanced with the increase in the temperature. The difference in
the temperature between the top and the underlying coal therefore increased gradually. Particularly after the 14th day (when such difference exceeded 10 °C), the heating rate at the top increased notably and soon it burned. That is, in real project, once the temperature difference (10 °C) between the upper and the lower of the coal is detected, or the temperatures for them show a distinct difference, protective and effective measures must be taken to avoid the potential fire disaster.

**Indicator gas**

In general, the main features of indicator gases are high sensitivity, stability and detectability (Shao and Dai, 1996). Among these various gases, CO and CO₂ are relatively more pronounced emission during this process (Baris et al., 2012; García-Torrenta, 2012). Figure 4 shows the variations of the average CO and CO₂ concentrations in the furnace for each day during coal spontaneous combustion.

As seen in Figure 4, both CO and CO₂ concentrations are shown to be strongly time-dependent. At the beginning, CO₂ concentration was at a high level due to coal desorption, then it decreased rapidly. However, there was no significant change in CO concentration, implying the coal experienced slow oxidations during this stage. Subsequently, both CO and CO₂ concentrations remained more or less constant for a long time, indicating a stable phase during the test. Until the 55th day, both concentrations gradually increased as well as the slope (tangential value of each point on the curves). This means that the coal has entered into the phase of accelerated oxidation. These characteristics of indicator gases are well in keeping with the temperature variation (Figure 3).

The obtained results indicate that during the process of coal spontaneous combustion, production rate of indicator gas differs as the temperature rises. The higher the temperature, the larger the production rate. Therefore, the production rates for different areas varies due to the difference in temperature. For instance, as shown in Figure 3, in 65th day the higher-temperature area was located at 127cm; accordingly, the corresponding production rate of various gases must be relatively large. In other words, in addition to the temperature monitored in situ, the variation of indicator gas concentration is also a reliable precursor for predicting the potential spontaneous combustion.

![Figure 4. The progressive variation of gas (CO, CO₂) concentration.](image-url)
Spatial and temporal variation of oxygen concentration

Oxygen consumption is generally proportional to the production of indicator gases (CO and CO$_2$), which could also reflect the degree of coal oxidation reaction. It is shown in Figure 4 that before 55th day, CO and CO$_2$ concentrations did not varied greatly but remained approximately constant except for the initial stage (coal desorption), which is also the case for oxygen consumption. Thus, only the last stage of the experiment (in which oxygen concentration shows a clear variation) was selected for analysis of oxygen consumption. Figure 5 demonstrates the dynamic variations of the oxygen consumption and the temperature at different heights from 64th day to the end. It is seen from Figure 5 that on

![Figure 5. The dynamic variations in oxygen concentration and temperature along the height of the furnace in the last stage. (a) The 64th day (b) The 66th day (c) The 68th day (d) The 69th day (e) The 70th day (f) The 71th day.](image)
the whole, oxygen concentration decreased as the distance (away from the bottom of the furnace) increased, implying the oxygen consumption was not the same but increased along the height of the coal (the slope stands for the degree of oxygen consumption). It is to note that the slope of oxygen concentration decreased more rapidly as time went by, corresponding to the accelerated stage as analyzed above. In comparison with the curves of the temperature, it was found that the higher the temperature, the lower the oxygen concentration, which is in good agreement with the above results. Besides, the rapid reduction in slope gradually appeared at around 127 cm in which the corresponding temperature is also getting higher, implying the coal oxidation reaction at 127 cm became progressively severe. Overall, the variation of oxygen concentration is in keeping with the analysis above.

**Spatial and temporal variation of oxygen consumption rate**

The oxygen consumption rate is the crucial characteristic parameter in coal spontaneous combustion as well (Kuenzer et al., 2012). Based on the experimental conditions (Nordon et al., 1979), some assumptions are made for quantitatively calculating the oxygen consumption rate: (1) the air flows uniformly along the vertical direction (z-axis); (2) the air velocity is constant in the furnace; (3) oxygen diffusion is not taken into account; (4) the temperature of the selected infinitesimal zone varies uniformly. According to the theory of mass transfer, the equilibrium equation of oxygen concentration in coal body can be expressed as follows (Xu, 2001):

\[ V(T) = u \frac{dC}{dZ} \]  

where \( V(T) \) is the oxygen production rate, \( \text{mol}/(\text{cm}^3\text{s}) \); \( u = Q/(Sn) \), is the average velocity of air in the void, \( \text{cm/s} \); \( C \) is the oxygen concentration, \%; \( Z \) is the distance away from the air inlet, cm; \( Q \) is the air flow, \( \text{cm}^3/\text{s} \); \( S \) is the cross sectional area, \( \text{cm}^2 \); \( n \) is void rate, %.

Generally, oxygen consumption rate is proportional to the oxygen concentration. Therefore, it read:

\[ V(T) = \frac{C}{C_0} V_0(T) \]  

where \( C_0 \) is the standard oxygen concentration, %; \( V_0(T) \) is oxygen consumption rate of coal in fresh air, \( \text{mol}/(\text{cm}^3\text{s}) \).

Substituting equation (1) into equation (2), equation (3) is obtained:

\[ \frac{C}{C_0} dC = V_0(T) \frac{Sn}{Q} dZ \]

Integrating both the sides of equation (3), equation (4) can be rearranged as:

\[ V(T) = \frac{QC_0}{Sn(z_{i+1} - z_i)} \ln \frac{C_t}{C_{i+1}} \]
where $C_i$, $C_{i+1}$ are oxygen concentrations at two positions, respectively, %; $z_{i+1}$, $z_i$ are the distances at two positions from the air inlet, respectively, cm. The calculated results for the oxygen consumption rates at different monitoring points are shown in Figure 6. Note that only the data (the last stage in accordance with Figure 5) are selected for comparison. As mentioned above, the oxygen concentration varies for different heights (Figure 5), which result in the difference in oxygen consumption rate (Figure 6). Since the higher oxygen consumption rate corresponds to the higher-temperature area, and the order of the occurrence of higher oxygen consumption rate matched that of higher-temperature area rather satisfactorily.

The effect of air supply rate

Generally, increasing the air supply rate could provide a higher level of oxygen concentration, but at the same time more heat generated are also taken away. Therefore, it is necessary to investigate the effect of air supply rate and then determine the appropriate level that meets the requirement of providing insufficient oxygen and meanwhile of taking heat generated away as more as possible. As a result, two additional experiments were also conducted to investigate how the air supply rate affect coal spontaneous combustion. Two different air supply rates are imposed: one was 0.8 L/min for group a; the other was 0.5 L/min for group b. To save the experimental time, a special type of coal sample (easier to combust) was used and the corresponding properties were listed in Table 2. The initial temperature of both experiments was set at 30°C. Temperature variations of the coal at different heights for the two groups were shown in Figure 7.

It depicts that on the whole, the higher-temperature area first appeared to be at the top of the coal, then moved towards the bottom and eventually burnt at approximately 73 cm.

![Figure 6. The oxygen consumption rates at different monitoring points in the last stage.](image)

| Coal samples | Particle size (mm) | Mass (kg) | Height (cm) | Humidity (%) | Ash (%) | Volatiles (%) | Calorific value (MJ/kg) | Porosity (%) |
|--------------|--------------------|-----------|-------------|--------------|---------|--------------|------------------------|-------------|
| a            | 6.42               | 62.6      | 198.0       | 14.1         | 15.5    | 31.8         | 27.6                   | 0.31        |
| b            | 6.51               | 52.37     | 198.3       | 15.4         | 16.3    | 34.6         | 30.8                   | 0.4         |
Both results were shown to be time-dependent. However, it did not take the same amount of
time to combust: 15 days for group a (0.8 L/min) whereas 18 days for group b (0.5 L/min).
This indicates that the spontaneous combustion period is strongly affected by the air supply
rate. The higher air supply rate could shorten coal spontaneous combustion. For conve-
nience in analysis, a comparison of the higher temperature of each day for the two groups
was made in Figure 8. One can see that there was no significant difference in temperature
(below 100°C), meaning oxygen concentration affected the results very little in low-
temperature stage. However, with the temperature rising, oxygen concentration gradually
became the main factor. This is because high temperature resulted in the increase in the
number of reactive functional groups, which requires a higher level of oxygen concentration.
Especially in the accelerated-oxidation phase (beyond 130°C), oxygen concentration has
been the key factor to restrict the potential combustion.

Figure 7. The temperature variations for different air supply rate: (a) 0.8 L/min; (b) 0.5 L/min.

Figure 8. The temperature comparison for different air supply rate: (a) 0.8 L/min; (b) 0.5 L/min.
To quantitatively identify the relationship between the temperature and time (Figure 8), the numerous trials have led to the following simple functions:

\[
T_1 = \frac{28.225}{1 - 0.04403t_1}
\]

(5)

\[
T_2 = \frac{31.026}{1 - 0.0587t_2}
\]

(6)

where \(T_1, T_2\) are the temperature of higher-temperature area, \(^{°}C\); \(t_1, t_2\) are the time, day. The corresponding fitting coefficient were 0.947 and 0.991, respectively. Obviously, \(T = a/(1 - bt)\) was the general form of the two equations (equations (5) and 6). When \(t = 0\), \(T = a\). The term \(a\) can be regarded as the initial temperature; with regard to the term \(b\), it is related to the factors (such as the air supply rate, oxygen concentration). Note that due to the limit of \(t\), this model is just applicable to the coal with strong spontaneous tendency.

**Conclusion**

The aim of this work is to provide a simple estimation of spatial and temporal variation of higher-temperature area during the coal spontaneous combustion. For this purpose, an adiabatic oxidation testing system was established to simulate the natural temperature rise. The obtained results show a strong dependence of the coal temperature on time. The coal mainly experienced three stages during coal spontaneous combustion: (i) slow-oxidation stage; (ii) accelerated-oxidation stage; (iii) combustion stage. The higher-temperature area first moved from the bottom to the top slowly, then stayed at the top until accelerated-oxidation stage is reached and eventually moved towards to the bottom rapidly. Higher air supply rate could shorten spontaneous combustion period and there exists a hyperbolic relationship between the temperature and time.

With regard to indicator gases, plenty of CO2 was generated due to coal desorption once the experiment started and then it decreased rapidly. During the slow-oxidation stage, both CO and CO2 concentrations remained more or less constant. Both gases increased rapidly after the coal has entered into the accelerated-oxidation stage. The corresponding oxygen consumption showed a proportional relationship to the production of CO and CO2. The results suggest that once the temperature difference (10\(^{°}C\)) between the top and bottom is detected, or there exists a large difference in the temperature between the monitored areas, great attention need be paid to preventing the potential spontaneous combustion disaster.

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Reference

Baris K, Kizgut S and Didari V (2012) Low-temperature oxidation of some Turkish coals. *Fuel* 93: 423–432.

Beamish BB, George JD and Barakat MA (2003) Kinetic parameters associated with self-heating of New Zealand coals under adiabatic conditions. *Mineralogical Magazine* 67(4): 665–670.

Benfell KE, Beamish BB and Rodgers KA (1997) Aspects of combustion behavior of coals from some New Zealand lignite-coal regions determined by thermo-gravimetry. *Thermochimica Acta* 297(1–2): 79–84.

Cheng W, Hu X, Xie J, et al. (2017) An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties. *Fuel* 210: 826–835.

Deng J, Xiao Y, Li Q, et al. (2015) Experimental studies of spontaneous combustion and anaerobic cooling of coal. *Fuel* 157: 261–269.

Fan JY, Liu P, Li JJ, et al. (2020a) A coupled methane/air flow model for coal gas drainage: Model development and finite-difference solution. *Process Safety and Environmental Protection* 141: 288–304.

Fan JY, Xie HP, Chen J, et al. (2020b) Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs. *Applied Energy* 258: 114007.

García-Torrent J, Ramírez-Gómez A, Querol-Aragón E, et al. (2012) Determination of the risk of self-ignition of coals and biomass materials. *Journal of Hazardous Materials* 213–214: 230–235.

Ge ZL, Zhang L, Sun JZ, et al. (2019) Full coupled muti-scale model for gas extraction from coal seam stimulated by directional hydraulic fracturing. *Applied Science* 9: 4720.

Jiang DY, Li L and Beamish BB (2008) The effect of moisture content on the tendency of coal to combust spontaneously. *Journal of Chongqing University* 31: 1451–1454.

Kuenzer C, Zhang J, Sun Y, et al. (2012) Coal fires revisited: The Wuda coal field in the aftermath of extensive coal fire research and accelerating extinguishing activities. *International Journal of Coal Geology* 102: 75–86.

Liu W, Qin YP, Yang XB, et al. (2013) Energy migration theory of spontaneous combustion in goaf. *Journal of China Coal Society* 38: 906–910.

Luo L, Zhang H, Jiao A, et al. (2019) Study on the formation and dissipation mechanism of gas phase products during rapid pyrolysis of superfine pulverized coal in entrained flow reactor. *Energy* 173: 985–994.

Ma HP, Lu W, Wang DM, et al. (2006) Research on physical adsorbed oxygen in coal spontaneous combustion processing. *Coal Science and Technology* 34: 26–29.

Peng HH, Fan JY, Zhang X, et al. (2020) Computed tomography analysis on clyclic fatigue and damage properties of rock salt under gas pressure. *International Journal of Fatigue* 134: 105523.

Ren TX, Edwards JS and Clarke D (1999) Adiabatic oxidation study on the propensity of pulverized coals to spontaneous combustion. *Fuel* 78(14): 1611–1620.

Ren X, Hu X, Xue D, et al. (2019) Novel sodium silicate/polymer composite gels for the prevention of spontaneous combustion of coal. *Journal of Hazardous Materials* 371: 643–654.

Shao H and Dai GL (1996) Optimal selection and application of indicator gas of coal spontaneous combustion. *Coal Science and Technology* 24: 43–46.

Song Z, Kuenzer C, Zhu H, et al. (2015) Analysis of coal fire dynamics in the Wuda syncline impacted by fire-fighting activities based on in-situ observations and landsat-8 remote sensing data. *International Journal of Coal Geology* 141–142: 91–102.

Wang J, Zhang Y, Xue S, et al. (2018) Assessment of spontaneous combustion status of coal based on relationships between oxygen consumption and gaseous product emissions. *Fuel Processing Technology* 179: 60–71.
Xu J (2001) *Determination Theory of Coal Spontaneous Combustion Zone*. Beijing, PR China: China Coal Industry Publishing House.

Yang Y, Li Z, Si L, et al. (2018) Study on test method of heat release intensity and thermophysical parameters of loose coal. *Fuel* 229: 34–43.

Zhang L, Ge ZL, Lu YY, et al. (2020) Tree-type boreholes in coal mines for enhancing permeability and methane drainage: Theory and an industrial-scale field trial. *Natural Resources Research* 29(5): 3197–3213.

Zhang Y, Li Y, Huang Y, et al. (2018a) Characteristics of mass, heat and gaseous products during coal spontaneous combustion using TG/DSC-FTIR technology. *Journal of Thermal Analysis and Calorimetry* 131(3): 2963–2974.

Zhang Y, Shi X, Li Y, et al. (2018b) Characteristics of carbon monoxide production and oxidation kinetics during the decaying process of coal spontaneous combustion. *The Canadian Journal of Chemical Engineering* 96(8): 1752–1761.

Zhou F, Li J, He S, et al. (2009) Experimental modeling study on the reignition phenomenon when opening a sealed fire zone. *Procedia Earth and Planetary Science* 1(1): 161–168.

Zhou FB, Shao H, Li JH, et al. (2010) Experimental research on combustion product formation during coal spontaneous combustion under reduced oxygen concentrations. *Journal of China University of Mining & Technology* 39: 808–812.