High-temperature area migration characteristics of loose coal spontaneous combustion based on experimental scale of semi-enclosed experimental system

Jingyu Zhao\(^1\), Tinghao Zhang\(^1\), Tao Guo\(^2\), Yuxuan Zhang\(^3\) and Jiajia Song\(^4\)

1 School of Safety Science and Engineering, Xi’an University of Science and Technology, 58, Yanta Mid. Rd., Xi’an, Shaanxi 710054, PR China
2 Emergency Administration Bureau of Xi’an High-tech Zone, Shaanxi Province, Xi’an, Shaanxi Province 710065, PR China
3 Shaanxi Coal Industry and Chemical Technology Research Institute Co., Ltd., Xi’an, Shaanxi 710065, PR China
4 Corresponding author’s e-mail: zhaojingyu90@xust.edu.cn

Abstract. According to the actual combustion characteristics of loose coal, and in view of the advantages and disadvantages of the existing research equipment for the high-temperature area, a simulated experimental device for the development of coal fire was designed and fabricated. The coal sample of Mengcun coal mine in Xianyang, Shaanxi Province China as the research object, the device was used to simulate the combustion of loose coal, and the distribution and movement of high-temperature area during the combustion were studied. The temperature change of the high-temperature area was obtained from normal temperature to ignition. The results showed that during combustion, the temperature rose first with the increase of time and then decreased. When the temperature reached 309.5 °C, the coal sample started to combustion. In addition, the temperature decreased to the ambient temperature after 600 h. The high-temperature area of the selected coal sample was concentrated in the middle part and the back part of the furnace, which was for the poor thermal conductivity, water evaporation of coal intrinsic quality. Moreover, the temperature decreases in turn during the downward propagation of the high-temperature area in the depth. And its decline to the limit oxygen concentration (1%~3%) is similar to reaching the combustion point temperature. Due to the influence of water content, pore and oxygen concentration, the movement of oxygen concentration and high temperature areas are mainly moved to the position and crack direction near the wind direction of coal-like combustion, showing nonlinear movement rules.

1. Introduction
Coal spontaneous combustion has a severe impact on human mining and physical and mental health, and causes a serious waste of resources. China attaches great attention to coal spontaneous combustion and formulates corresponding policies and measures according to the actual situation [1]. A series of achievements had been made in prevention and control of coal spontaneous combustion, and the detection of temperature field. Scholars had also established a large number of models to simulate the development and change of temperature field during coal fire, such as the steady state transformation of the temperature field model [2] and two-dimensional mathematical model [3]. Bian et al. [4-5] simulated the mathematical model of temperature field by using finite difference in
numerical method. It was found that the temperature of coal increased exponentially with time due to oxidation and exothermic heat, and the temperature field around the heat source points changed with time. Song et al. [6] simulated the effect of air leakage channel on the range and temperature of coal fire combustion area. At the same time, scholars also detected the environmental factors such as solar radiation [7-9], atmospheric changes and water during the process of coal spontaneous combustion in high temperature areas, and established the conduction equation of coal spontaneous combustion at high temperature points [10-12]. In addition, a fire model was built to simulate the whole fire area, predecessors also studied the gas molecules in the fire area [13]. Wang et al. [14] simulated the distribution of temperature field, carbon monoxide concentration, and velocity field in a fire area when the spontaneous combustion center formed and spread under the condition of ignoring the change of coal and rock permeability. Wen et al. [15] reported that there was radon precipitation in loose coal during combustion by isotope test, while radon precipitation increased exponentially with the increase of temperature, and had a critical temperature. Li et al. [16] simulated the entire process of loose coal spontaneous combustion from normal temperature to ignition temperature, and obtained that the high-temperature points first appeared in the low oxygen concentration distribution area, and then gradually moved to the high positive concentration distribution area. Zhao et al. [17] realized the real-time on-line monitoring of gas concentration at multiple sampling points by time-sharing and automatic switching channels.

However, because the combustion conditions of loose coal are complex and the movement law of temperature field is unclear, previous studies mostly focused on the construction of function model and the simulation analysis of the formation process of high temperature point of coal spontaneous combustion. But there was no unified understanding of the migration mechanism of high temperature area of coal fire, and little attention was paid to analyzing the evolution process of high temperature area in the development process of loose coal combustion from the experimental scale. Therefore, in this paper, a self-developed simulation experimental system of coal fire development and evolution is used to study the position movement and change law of high temperature area during the development of loose coal combustion. The research results clarify the development and spread law of loose coal combustion, and determine the change law of oxygen volume fraction at high temperature points, which provides a theoretical basis for the prevention and control of spontaneous combustion of loose coal in coal pile, mining coal and coal storage state.

2. Experimental

2.1. Semi-enclosed experimental system for simulating a coal fire

The experimental system included the following devices: temperature control and monitoring system, hydraulic device, coal spontaneous combustion simulation furnace, gas analysis system, and pollutant treatment system. The coal spontaneous combustion simulation furnace consisted of high-temperature resistant pure fiber blanket and carbon steel material pressing with high flexibility. The furnace structure is exhibited in Figure 1. The inner dimensions of the furnace were 300×300×600 mm, thickness of insulation layer on both sides of wall. The insulation layer consisted of a mixture of refractory bricks and fibers, which had a thermostability of 1200 °C, and the temperature uniformity in the furnace was mastered at ±10 °C. To scrutinize the temperature distribution and development during the experiment, a through hole with a diameter of 16 mm was arranged around the furnace wall as the temperature data acquisition points and the gas acquisition points. The temperature measuring unit was connected with the temperature recorder device, and the collected gas was analyzed by gas chromatograph.

Three stainless steel heating rods were arranged evenly on the surface of the coal to avoid the influence to the measuring point. By heating the coal surface to form a sound thermal storage environment to ensure the happening of spontaneous combustion. The temperature sensor adopts WRNK-19(K) sheathed thermocouple that had the temperature range of 0–1100 °C, and the temperature stability was controlled at ±1 °C. A temperature control and monitoring platform was
used to monitor the temperature change of each measuring point in coal in real time. In addition, the flue gas produced by the experiment was gleaned and treated by pollutant treatment system.

![Figure 1. Semienclosed experimental system.](image)

![Figure 2. Measuring point layout.](image)

![Figure 3. TG and DTG curves of different coal samples under air atmosphere](image)

2.2. **Experimental process**

The coal sample of Mengcun coal mine was used in the experiment. The coal quality analysis is listed in Table 1. The volatile content of the coal sample was 33.51%, more than 18%, and the risk of spontaneous combustion was great [18]. The loose coal samples were uniformly arranged in the coal spontaneous combustion simulation furnace, the ambient temperature and humidity were recorded under natural ventilation. Thermocouple and heating unit were arranged through the hole of the furnace.

| Table 1. Analyses of proximate and ultimate of samples. |
|---------------------------------------------------------|
| **Coal sample** | **M<sub>ad</sub>** | **A<sub>ad</sub>** | **V<sub>ad</sub>** | **FC<sub>ad</sub>** | **C** | **H** | **O** | **N** | **S** | **H/C** |
|-----------------|------------------|------------------|------------------|------------------|------|------|------|------|------|--------|
| Mencun          | 4.41             | 14.07            | 33.51            | 48.01            | 78.84| 4.75 | 14.2 | 1.37 | 0.84 | 0.72   |

The length of thermocouple was 400 mm. To achieve uniform detection of coal in different positions of temperature, the above arrangement was mainly used to monitor the change of temperature with time, and to find the movement of high-temperature area in coal fire. The layout of temperature measuring points in coal is shown in Figure 2. The distance from the left side to the right side of the wall in the furnace is displayed in Table 2. Three points per layer, the distance was 50, 150, and 250 mm, respectively. Layout of five-story measuring points, a total of 15. Here, thermocouple numbers 1, 4, 7, 10, and 13 are indicated by red in Figure 2, 250, 50, 250, 50, and 250 mm from the left to the right; thermocouple numbers 2, 5, 8, 11, and 14 were marked by green in Figure 2, 50, 250, 50, 250, and 50 mm; thermocouple numbers 3, 6, 9, 12, and 15 were indicated by blue, 150 mm. The distance between two thermocouple was 100 mm in the same layer, and 70 mm in vertical layer.

3. **Analysis of the oxidative and spontaneous combustion stage**

In order to better analyze the temperature shift characteristics, the thermal weight curve characteristic temperature points are selected [19], and the oxidative and spontaneous combustion process is divided into stages according to the characteristic temperature. Figure 3 shows the TG and DTG curves of the experimental coal sample. The temperature range of three different oxidation and spontaneous combustion stages of Mengcoal samples was shown in Table 2 below.
Table 2. Division on temperature stage of spontaneous combustion of two coal samples.

| Number | Oxide spontaneous combustion stage                                      | Average temperature range/℃ |
|--------|-------------------------------------------------------------------------|------------------------------|
| stage 1| Slow oxidation stage                                                   | 0–111                       |
| stage 2| Fast heating stage                                                      | 111–303                     |
| stage 3| High temperature spontaneous combustion stage                           | 303–604                     |

4. Results and discussion

4.1. Analysis of movement in high-temperature area

When the temperature of a certain measuring points exceeded the ignition temperature for the first time, the coal sample around this point reacted violently with oxygen and the oxygen consumption was large. It was determined that the area where the measuring point was located as a high-temperature area, and this measuring point was a high-temperature point.

The temperature change of 15 measuring points of test coal sample is shown in Figure 4 and Figure 7. It could be seen that the change trend of the three measuring points in each layer was basically similar. At the beginning of the experiment, the temperature variation of each measuring points was small, and the temperature was close to the ambient temperature. The temperature moved downward with the increase of time, and the temperature would decrease accordingly in vertical direction, mainly because the thermal conductivity of coal was weak. Because the ambient temperature was low and without external heat source, the temperature decreased gradually. The heat accumulation took a long time and the heat transfer rate was slow in the early stage of Mengcun coal experiment. The temperature of the first two layers of coal was relatively low. After 300 h, the bottom coal combustion was basically finished.

The high-temperature area of Mengcun coal developed from the azimuth of measuring points 2, 5, 7, 10, and 13, as shown in Figure 5. The high-temperature area was concentrated in the middle and west directions of the furnace. The surface coal were ignited to a burning state, the first measuring point was close to the surface. Point 2 site was obviously affected by the wind flow in the environment, the coal in this area reached the ignition point and accelerated the coal-oxygen complex reaction, caused the benzene ring to break in the coal molecule, released heat and gaseous products, first formed a high-temperature area, the exothermic amount increased prominently. At 12 h, cracks occured which provided ventilation for the propagation of high-temperature areas, promoting the high-temperature area formed with the direction of fracture development. High temperature area appeared at point 5. Roughly 15 h later, the oxygen channel continued to move down non-linearly, the high-temperature area appeared at point 7 at the same position as point 5 in layer 2. Coal samples released a large amount of heat at this location for the complete reaction with oxygen. The high-temperature area after 20 h was located near point 10, 50 mm from the right side of the furnace. The position below the 7th measuring point should be in a high-temperature state. After 26 h, high-temperature area reached the bottom of the experimental device at point 13, 250 mm from the inner wall on the right side of the furnace. After 480 h, the temperature points of 1–15 were around 10 °C. At 600 h, the temperature of each measuring point was close to the ambient temperature, which was concluded that the combustion period of Mengcun coal was ca. 600 h.

The continuous supply of oxygen was an important condition to maintain the combustion of loose coal. Under the condition of natural ventilation, the experiment not only simulated the actual situation of opencast mine, but also provided sufficient oxygen to maintain the combustion. Loose coal was porous medium, with which the heat conduction was a comprehensive process, which belonged to unstable heat transfer. With the increase of time, the heat moves downward from shallow to deep area. Due to the effect of physical adsorption and fracture, oxygen would first propagate down the direction of the most diffused fracture after the surface coal come to combust,
causing that the measuring points rose to the ignition temperature. With the deepening of combustion depth, the chemical reaction of coal oxygen was intensified, the heat storage capacity was enhanced, and the heat transfer effect was decreased saliently. When the fracture position changed, the high-temperature area changed and moved to the deep area, but the temperature was lower than the upper layers.

The temperature change of the first and second layers of coal samples was mainly affected by the air flow and heat convection, which led to the similar characteristics temperatures. The high-temperature area moved downward from layer three to five nonlinear with the influence of crack, porosity, oxygen concentration, and intrinsic factor of coal sample.

4.2. Analysis of oxygen change rules

The above analysis and determine the high temperature area are 2, 5, 7, 10 and 13 respectively, so analyze the oxygen concentration changes in this section. Due to the slow spontaneous downward heat transfer of the coal body, the gas was started when a layer had a measurement point higher than 30℃ during the test. When the measurement point temperature of layer 5 reaches 312.3℃. The temperature has exceeded the combustion point temperature, it is considered that layer 5 has appeared a high temperature area, and the gas extraction is stopped.

With increasing depth, the oxygen concentration in each layer begins to decrease from shallow to depth. Compared with Figure 6, the first time point when the oxygen concentration in the high temperature region of each layer drops to 1% ~3% is similar to the time point of reaching the combustion point temperature. The time experienced during the period of decreasing oxygen concentration in high temperature regions gradually increases with increasing depth. Notably, the starting time difference of the decreased oxygen concentration region in the second layer and the third layer is 1 h, which basically corresponds to the time when its ignition point appears. Compared with the oxygen concentration changes in the high temperature area of each layer, the fifth oxygen concentration is maximum when the temperature begins to increase, and other high temperature areas basically decrease with the increase of depth. Because the first layer has the large contact area, the most intense combustion and the oxygen concentration is the lowest.

The natural ventilation state not only simulates the actual situation of the open-air mine, but also provides sufficient oxygen to maintain the experimental coal-like combustion. When combustion begins to form, it will gradually develop from shallow to deep. Since the loose coal body in the experimental device is mainly porous medium, the heat transfer of each site is a comprehensive heat transfer process of conduction, radiation and convection, which belongs to unstable heat transfer. With the increase of time, the heat source keeps moving downward. Due to the influence of physical adsorption and cracks, after the surface coal combustion, the oxygen will first spread downward along the direction of the most easily diffusive crack [20], leading to the spontaneous combustion of the coal sample near the crack, and the temperature of the measurement point area rises and reaches the combustion point. With the deepening of combustion depth, the coal oxygen chemical reaction intensifies, the heat storage capacity increases, and the heat transfer increases significantly. When the fracture position changes, the high temperature area changes and moves to deep.

From the above analysis, the temperature changes of the first and second layers are mainly affected by the environmental flow and coal combustion cracks, resulting in the first two coal samples are relatively similar; the temperature changes of the third, fourth and fifth layers are mainly affected by the cracks and the heat transfer, and the temperature decreases. All the high temperature region moved downward during the experiment, and due to the pore, oxygen concentration, the whole propagation direction of the coal sample itself.
Figure 4. Temperature situation of each measuring point of Mengcun coal sample at the same time.

Figure 5. High-temperature area migration and distribution of Mengcun coal sample.

Figure 6. Trend of oxygen concentration over time.

(a) Temperature versus time curve at points 1–3
(b) Temperature versus time curve at points 4–6
(c) Temperature versus time curve at points 7–9
(d) Temperature versus time curve at points 10–12
(e) Temperature versus time curve at points 13–15

Figure 7. Temperature of each measurement temperature over time.
5. Conclusions
A semi-enclosed experimental system was developed for simulating the coal fire, the movement law of high-temperature area of loose coal during spontaneous combustion was analyzed, and the following conclusions were drawn:

Based on the study of the movement law of the high-temperature area during coal spontaneous combustion and drawing on the advantages and disadvantages of the existing equipment, a simulated experimental system for studying the development of coal fire was designed and fabricated. It can satisfy the study of combustion characteristics in different high-temperature stages under different conditions.

With the increase of time, the temperature of the selected Mengcun coal was changed vertically in the direction of air flow and cracks in coal spontaneous combustion. When the temperature of the coal sample propagated downward, the first time in the high-temperature area first commenced at the 5th h, and at 26 h, the high-temperature area reached the bottom of the experimental coal. The combustion period was 600 h. The high-temperature area was concentrated in the middle and west parts of the furnace.

The oxygen concentration reaches the limit oxygen concentration is basically the same time as the coal body reaches the combustion point. During the whole experiment, the shallow coal sample temperature was greatly affected by the environmental romance, the oxygen concentration decreased rapidly, and the deep coal sample temperature was greatly affected by the cracks and heat transfer. Compared with the shallow coal sample, the oxygen concentration decline time was delayed and the decrease rate was slower. Due to the influence of the water content, pore and oxygen concentration, the oxygen concentration and the high temperature area movement mainly move to the position near the wind flow and the crack direction of the coal sample combustion, showing a nonlinear movement law.

Acknowledgements
This study was sponsored by the National Natural Science Foundation of China of China (No. 5180-4246).

References
[1] Wang T, Zhang B, Wang QW, et al. 2017 Concept and connotation of green coal resources in China Coal Geol & Explor 45 1–9
[2] Tan B, Niu HY, He CN, et al. 2013 Goaf coal spontaneous combustion temperature field theory and numerical analysis under mining conditions. Journal of Central South University (Science and Technology) 44 381–387
[3] Wolf Karl H, Bruining H. 2007 Modeling the interaction between underground coal fires and theirs roof rocks. Fuel. 86 2761–2777
[4] Bian XK, Bao ZH, Shi MR 2000 Numerical simulation of temperature field for worked-out section of coal mines and prediction of spontaneous combustion J N Univ Technol 22 43–47
[5] Lu GD, Zhou XQ, Jiang J 2008 A mathematical model of the temperature in a coalfield fire area Journal of China University of Mining & Technology 18(3) 358–361
[6] Song ZY, Zhu HQ, Tan B, et al. 2014 Numerical study on effects of air leakages from abandoned galleries on hill-side coal fires. Fire Safety J 69 99–110
[7] Rosema A, Guan H, Veld H 2001 Simulation of spontaneous combustion, to study the causes of coal fires in the Rujigou Basin Fuel 80 7–16
[8] Chu TX, Li P, Yu MG, et al. 2017 Numerical simulation of thermal conductivity of loose coal under water phase transition J China Coal Soc 42 1782–1789
[9] Song DY 2012 Research on the inversion technique recognition of hidden fire source in coal seam based on infrared imaging exploration Xi’an University of Science and Technology
[10] Wang ZP, Cheng WM, Xin S, et al. 2003 The calculation of close-range coal inflammation position at coal-roads based on infrared detecting and inverse heat conduction technology J
China Coal Soc 28 603–607

[11] Cai CF 2017 Experimental study on similar simulation of temperature field and stress field evolution process in coalfield fire Xi’an Univ Sci Technol

[12] Deng J, Xu JC, Zhang XH 1999 Dynamic computer simulation of temperature field in goaf areas of fully-mechanized roof-coal caving face [J] Journal of China University of Mining & Technology 28 179–181

[13] Xiao Y 2013 Study on the mechanical characteristics of coal-rock mass of coalfield fires with thermo-hydro-mechanical coupling for fissure seepage Xi’an Univ Sci Technol

[14] Wang HY, Zhou XQ, Zhang HJ, et al. 2010 Seepage thermal dynamical coupling model for spontaneous combustion of coalfield outcrop and its application Journal of University of Science and Technology. Beijing 32 152–157

[15] Wen H, Cheng XJ, Xu YH, et al. 2019 Law of radon precipitation and migration in loose coal during spontaneous combustion process J China Coal Soc 44 2816–2823

[16] Li L, Chen JC, Jiang DY, et al. 2016 Experimental study on temporal variation of high temperature region and index gas of coal spontaneous combustion J China Coal Soc 41 444–450

[17] Zhao XH, Sun PS, Yang Y, et al. 2020 Application in on-line monitoring system of gas concentration of coal spontaneous combustion index J China Coal Soc 1–10

[18] Xu JC 2001 Determination theory of coal spontaneous combustion zone Beijing, China coal Industry publishing house

[19] Hamid Siddiqi M, Liu XM, Tayyab Q, et al. 2020 Performance analysis of bio-fuel blends for clean energy production: Thermogravimetric analysis J Clean Prod

[20] Lü HF, Deng J, Li DJ, et al. 2021 Effect of oxidation temperature and oxygen concentration on macro characteristics of pre-oxidised coal spontaneous combustion process Energy 227