Characteristics for Oxygen-Lean Combustion and Residual Thermodynamics in Coalfield-Fire Zones within Axial Pressure

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ABSTRACT: Coalfield fires during coal mining have become a major problem in the world today. To effectively prevent such disasters, we established an experimental platform to measure the spontaneous combustion characteristics of large-scale pressurized coal; thermal analysis experiments and microscopic analysis of briquettes under different axial pressures were carried out. It can be seen from the results that when the axial pressure is 4 MPa, the heating rate of the oxidative combustion of coal samples is accelerated, the crossing point temperature is lower (reduced by 71.09 °C), the activation energy is reduced (the second stage is decreased by 21.3 kJ/mol), and the oxidative combustion is more intense. Simultaneously, the porosity evolution process of briquettes under different axial pressures is simulated. Through calculation, it can be seen that the porosity and thermal conductivity show a linear increasing trend. The basis for the increase in the internal oxygen supply channels and increase in oxygen consumption when the axial pressure is 4 MPa is given. Through thermogravimetric–differential scanning calorimetry analysis, it is found that the maximum mass loss rate and maximum mass growth rate of residual coal after combustion under an axial pressure of 4 MPa are low, the residual rate after combustion is large, and the flammability rate is low when reoxidized, while complete combustion oxidation releases more heat. The application of axial pressure will change the combustion characteristics of briquettes, and the promotion effect is more obvious at 4 MPa. Analyzing the laws of the coal–oxygen composite reaction under different axial pressures provides theoretical guidance for the prevention and control of multistress coupling fields in coalfield-fire areas.

1. INTRODUCTION

China is rich in coal resources and is one of the largest coal producers in the world. At present, China’s energy situation is still “rich in coal, poor in oil, and low in gas.” Coal will continue to play a dominant role as China’s primary form of energy composition. This situation will remain difficult to change in the coming decades. Because coal reserves are much larger than other fossil fuel reserves, coal is an important energy source to meet future power needs.1−5 However, along with the development of coal production worldwide, especially in China, coalfield fires occur frequently. As a persistent threat to major coal-producing countries, coalfield fires are commonly distributed in exposed coalbeds with long-burning histories.6−9 The process of coalfield fire burning not only wastes a large amount of coal resources but also produces various toxic and harmful gases that pollute the atmosphere and seriously threaten human health.7−9 The interference of stress during the mining process destroys the balance of the original stress zone, and the coalfield-fire zone evolves and forms under the coupling of temperature, stress, flow, and other fields,8−10 bringing greater resistance to coalfield fire prevention.

At present, relevant scholars have revealed experimental and numerical calculation methods for coalfield fire prevention. Zeng et al.11 put forward a mathematical solution to define the equivalent permeability for elements in a coal-fire zone and presented a new method to calculate the oxygen consumption rate. Elick12 proposed that sinkholes and fractures occurred in the re zone and

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was approximately proportional to the square root of the average permeability. Wang et al.\textsuperscript{15} established a model coupling seepage with thermal dynamics for coalfield fires and concluded that the combustion center centralizes near the roof and quickly spreads in the outcrop direction. Ma et al.\textsuperscript{16} systematically analyzed the development and evolution of coalfield-fire areas from the perspective of multifield coupling. This study revealed the coal–oxygen composite chemical field involved in the process of coalfield fire zone development and evolution, the temperature field formed by the exothermic heating of the reaction, and the action mechanism between the stress field that deforms the coal and rock mass because of thermal stress and the gas seepage field through convection through the fissures.

Some scholars have discussed the process of applying stress coupling between the briquettes and coal rock. Tan et al.\textsuperscript{17} and Yin et al.\textsuperscript{18} discussed the influence of in situ stress on coal gas permeability based on the briquette test. Li and Xian\textsuperscript{19} studied the permeability characteristics of coal bodies under different temperature and stress conditions and believed that temperature and stress have different effects on the permeability characteristics of coal and rock bodies. Under different stress conditions, temperature can cause internal expansion of coal and rock bodies. The effect can also produce an external expansion effect. Mckee et al.\textsuperscript{20} analyzed the relationship among the permeability, porosity, and effective stress of fractured coal and rock mass and obtained the relationship among the changes in internal parameters. Peng et al.\textsuperscript{21} investigated the dissipated, released, and residual energies of coal specimens by conventional triaxial compression tests using five different confining pressures and found that the failure energy ratio was approximately linearly related to the fractal dimension of the coal fragments.

For the prevention and control of coalfield fires, most scholars study the permeability characteristics of coal and rock bodies under the combined actions of temperature and stress, the thermal destruction characteristics of rock mass under the combined actions of stress and temperature, and the developmental laws of fissures. We know that part of the reason for the formation of coalfield-fire zones is that loose coal that collapses in the mined-out area is susceptible to an increased squeezing density, resulting in coalfield fires after changes in the surrounding heat sources. At present, there are many studies on raw coal but few studies on the spontaneous combustion characteristics of briquettes. The combustion characteristics of particulate coal under different axial pressures have been preliminarily determined, but some combustion characteristics of briquettes and changes in pores during combustion have yet to be studied. Because of the small difference in the pore crack structure of coal compared with that of the original coal,\textsuperscript{22} this paper constructs coal briquettes and uses the programmed temperature control system (ACTP) to simulate the combustion characteristics of a coalfield-fire area under different stress conditions. According to previous studies\textsuperscript{23} on the thermogravimetric variation of different oxygen concentrations, the internal micropore structure evolution process was analyzed and combined with thermogravimetric (TG)–differential scanning calorimetry (DSC) analysis of residual coal after combustion to establish the oxidative combustion characteristics of briquettes under different axial pressures. This study provides a theoretical basis for the prevention and control of spontaneous combustion disasters in coalfield-fire areas affected by different load stresses during coal mining.

2. EXPERIMENTAL RESULTS AND ANALYSIS

2.1. Analysis of the Oxidation Heating Process. Taking the temperature of the central measuring point as the research object, the images of the oxidation heating process and the corresponding heating rate under different axial pressures are plotted, as shown in Figure 1a,b. It can be seen from the heating process under different axial pressures that the time required for the coal pillar to reach a predetermined temperature appears to first increase, then decrease, and finally increase. When the shaft pressure is 4 MPa, the time required to reach the predetermined temperature is less, indicating that the overall oxidation process is faster during the temperature increase period. The temperature change of the crossing point can also reflect the process of coal pillar spontaneous combustion oxidation.\textsuperscript{24} It can be seen from Table 1 that at

![Figure 1. Temperature change curve of the coal sample under different axial pressures: (a) heating process and (b) heating rate.](https://dx.doi.org/10.1021/acsomega.0c03108)
4 MPa, the crossing point temperature is lower, 86.92 °C, and the low-temperature oxidation process is faster at this time. On the whole, as the applied axial pressure increases, the heating rate first decreases and then increases. Compared with other axial pressure conditions, the heating rate is greater when the axial pressure is 0 MPa and there is a slight increase at 4 MPa. Because the heating rate is determined by two factors, heat transfer and oxidation, as the axial pressure increases, the tightness of the pores increases, resulting in a reduction in the contact area between the coal and oxygen, which weakens the oxidation reaction between the coal and oxygen. Therefore, the value of the maximum heating rate is reduced. When the axial pressure is 4 MPa, the pressure causes cracks in the coal pillars, which can increase the coal-oxygen binding area and further promote heat absorption, thereby slightly accelerating the heating rate. In the early stage of the oxidation temperature rise, the pressure increases the contact area, which makes the temperature rise faster. When the axial pressure is 4 MPa, the maximum temperature rise rate occurs at a higher temperature than at other axial pressures, indicating that a specific temperature will accelerate the oxidation rate.

The oxidation heating process is accompanied by oxygen consumption, and the change in the oxygen volume fraction is usually used to measure the severity of coal combustion oxidation. According to the change in the oxygen volume fraction at the outlet under each temperature gradient, the changes in the oxygen volume fraction and the oxygen consumption rate at the outlet of the briquettes under different axial compression strengths are shown in Figure 2a, b. The formula for the oxygen consumption rate is as follows

\[ V_{O_2}(T) = \ln \left( \frac{20.9\%}{C_{O_2} S} \right) \times \frac{20.9\% Q}{SL} \] (1)

In this formula, \( V_{O_2}(T) \) is the oxygen consumption rate, mol/(cm\(^2\)/s); \( L \) is the height of the coal sample in the vessel, cm; \( Q \) is the experimental air flow, 120 mL/min; \( S \) is the cross-sectional area of the vessel, cm\(^2\); and \( C_{O_2} \) is the oxygen concentration value at the outlet, %.

The change in briquette oxygen consumption under different axial pressures can be divided into two stages. The first stage is the accelerated oxygen consumption period. In this stage, as the oxidation temperature rises, the combustion oxygen absorption increases rapidly and the oxygen consumption rate decreases linearly. As the oxidation process continues, the second stage of the oxygen consumption plateau (after 188 °C) is reached. At this time, the coal-oxygen reaction is basically affected by the oxygen supply concentration and its own oxidation limit, and the oxygen consumption reaches a relatively stable state. It can be seen from the oxygen concentration change curve that there are relative differences for different axial pressure changes. During the accelerated decrease in the oxygen consumption at the outlet of stage 1, the oxygen consumption of a briquette at an axial pressure of 4 MPa increases and the oxygen content decreases rapidly. During the stationary phase, the oxygen consumption rate of coal samples at an axial pressure of 4 MPa is significantly higher than that of other coal samples. This is mainly because during the application of axial pressure, the internal structure of the briquette changes, some the macromolecular groups break, and the coal and oxygen contact area increases. Second, the briquette structure after rupture is looser, and the heat increases faster, which accelerates the consumption of oxygen. As the axial pressure increases, the coal sample with the original pore structure becomes tighter and oxygen consumption decreases. From the change in oxygen consumption under different axial pressures, it can be seen that the briquette oxidation speed is greater under an axial pressure of 4 MPa and the coal-oxygen reaction process is faster.

It can be seen from Figure 2a that axial compression changes the oxygen volume fraction in the briquette oxidation process and that the oxygen consumption shows a regular change with the axial pressure. In Figure 2b, according to the calculated oxygen consumption rate, the curve fitting the oxygen consumption rate with temperature changes was graphed, and the curves for different axial pressures were all found to fit an exponential function. The exponential function \( y = a(1 - e^{bx}) \) is used to fit the change in the oxygen consumption rate with temperature, and \( R^2 \) is between 0.97 and 0.99. The fitting formula is shown in Table 2.

According to the fitted graphs, the difference in the oxygen consumption rate under each axial pressure is obvious, and there is a trend of first increasing and then decreasing with the increase in axial pressure as a whole. It can be seen that when the axial pressure is 4 MPa, the image is above the other axial pressure images and the oxygen consumption rate is relatively
large. When axial pressure is applied, the fitted trend graph is relatively similar and the trend graph without axial pressure is relatively different. The main reason for this difference is that in the process of applying axial pressure, there is an increased contact area with the furnace wall and improved heat transfer from the furnace wall and the oxygen consumption rate increases earlier during low-temperature oxidation. However, the coal pillars at 0 MPa showed a significant growth trend before and after 125 °C, and there was more space remaining in the cranial cavity, resulting in a reduction in the heat transfer effect. Overall, after 188 °C, the rate of increase in the oxygen consumption rate begins to slow. At this time, the oxygen concentration limits the progress of the oxidation reaction, but the oxygen consumption rate is still relatively large at 4 MPa over a relatively stable period. Between 500 and 700 °C, the fixed carbon in coal is almost burned out. Inputting 500 °C into the exponential function formula provides the change in the limit value of the oxygen consumption rate as the axial pressure increases. The limit value of the oxygen consumption rate that is reached when the axial pressure is 4 MPa is 1191.4 mol/(cm³.s). The change in the oxygen consumption rate reflects the speed of the oxidation heating process. When the axial pressure is 4 MPa, the internal heat transfer and oxygen supply channel indicators are changed and the oxidative combustion is more intense.

When the heat produced by the composite reaction between the experimental coal sample and oxygen is greater than the heat dissipated, the experimental coal sample will spontaneously ignite. The composite reaction of coal and oxygen during low-temperature oxidation determines the difficulty of spontaneous combustion of the experimental coal sample. Activation energy is an indicator that reflects the speed of a chemical reaction. Here, the apparent activation energy of the experimental coal sample during low-temperature oxidation can be used to characterize the spontaneous combustion tendency of the experimental coal sample. According to the derivation formula, it can be obtained that ln\[\frac{C(O)P - C(O)}{C(O)P} \] and 1/T have a linear relationship, and the apparent activation energy E of the experimental coal sample under different axial pressures is calculated as shown in Figure 3. According to the changes in oxygen consumption, the activation energy can be calculated in two stages. It can be seen that the activation energy first decreases and then increases with the increase in axial pressure. When the axial pressure is 4 MPa, the activation energy is lower than that of other coal samples. The activation energy of the second stage decreases from 30.07 kJ/mol at 0 MPa to 8.77 kJ/mol at 4 MPa. These results show that the application of axial pressure can change the apparent activation energy of briquettes and that the application of axial pressure in the second stage has a stronger influence on the change in activation energy. Because coal molecules have stronger oxidation activity when the activation energy is lower, they easily react with oxygen; when the axial pressure is 4 MPa, spontaneous combustion is more likely to occur.

### Table 2. Fitting Formula of Change in Oxygen Consumption During Briquette Heating

| axial compression/MPa | fitting formula | R² |
|----------------------|----------------|----|
| 0                    | \(y = 821.4(1 - e^{-0.0034x})^{0.86}\) | 0.992 |
| 2                    | \(y = 1028.3(1 - e^{-0.0075x})^{0.84}\) | 0.993 |
| 4                    | \(y = 1192(1 - e^{-0.0035x})^{0.87}\) | 0.979 |
| 6                    | \(y = 1120.7(1 - e^{-0.0063x})^{0.87}\) | 0.988 |

![Figure 3. Changes in activation energy of oxidative combustion of the briquette under different axial pressures.](image)

![Figure 4. Average porosity of coal within the axial compression.](image)
Compared with other axially pressed coal samples, the oxidation heating rate is faster and the oxidation heating process is relatively stable. When an axial pressure of 2 MPa is applied, the pore structure is relatively dense and the porosity decreases relatively more than that without axial pressure applied (0 MPa). At this time, a small amount of the broken inorganic molecular structure appears, and the pores between the inorganic molecules decrease, resulting in a reduction in the coal–oxygen adsorption area. As seen in the smaller oxygen consumption rate in Figure 2, the reduction in pores affects the speed of the oxidation process. When the axial pressure is 4 MPa, the pore structure becomes increasingly dense. Because of further pressurization, the macromolecules have more cracks and there are many more oxygen supply channels in the structure. The porosity increases, the inorganic mineral molecules in the coal increase in fragmentation, and the aroma-group-like molecules become more dismembered, resulting in acceleration of the oxygen consumption rate and oxidation heating process. When the axial pressure is 6 MPa, the internal structure of coal molecules is closer, the porosity will be reduced compared to that at 4 MPa, and the coal oxygen contact area will be reduced; in turn, the progress of the coal–oxygen composite reaction is reduced. On the other hand, in the oxidation process, most of the reactions involve internal free radicals. With the increase in axial pressure (up to 4 MPa), the internal generation of free radicals is accelerated, making the coal–oxygen reaction more intense.

Changes in the pore structure of coal will affect changes in thermal conductivity. To further investigate the oxidation of briquettes under different conditions, the thermal conductivity of coal samples under different axial pressures is calculated as shown in Figure 6. Because the coal temperature reaches the critical temperature of coal self-heating at 70 °C, eq 2 is used to calculate the thermal conductivity ($\lambda$) of the coal sample before the critical temperature of self-heating. When the temperature of coal exceeds the critical temperature of coal self-heating, a violent oxidation reaction occurs, as calculated by formula 3 (where "$n$" is the porosity and "$q$" is the heat release intensity of the coal sample).

\[ \rho C \frac{\Delta T}{\Delta t} = \lambda \frac{T_2 - T_1}{\Delta x} \]

\[ \rho C \frac{\Delta T}{\Delta t} = \lambda \frac{T_{OV} - T}{\Delta x} + (1 - n)q \]

Figure 5. Evolution process of the coal pore structure under different axial compression conditions: (a) 0, (b) 2, (c) 4, and (d) 6 MPa.
In the early stages of the oxidation reaction (before 60 °C), the thermal conductivity is low under all axial pressure conditions. This is due to the heat dissipation during the internal transport of coal molecules from the desorption of gases and evaporation of internal moisture. After entering the violent oxidation reaction, the macromolecular groups in the coal are burned strongly by oxygen absorption and the thermal conductivity begins to increase sharply, which is in good agreement with the results for oxygen consumption of oxidation combustion in Section 2.1. Overall, the thermal conductivity of each coal sample reaches the maximum value at approximately 230 °C. Compared with other axially pressed coal samples, the thermal conductivity reaches the maximum when the axial pressure is 0 MPa. At this time, the oxidized coal samples are looser (Figure 5a), and when the porosity is larger, the area of the coal–oxygen contact is also larger. After axial pressure is applied, the thermal conductivity at 4 MPa is higher than that of other coal samples treated with axial pressure. This is mainly because the axial compression force caused the coal macromolecules to rupture, resulting in more

![Figure 6](image_url)

**Figure 6.** Variation in $\lambda$ by varying temperature under different axial pressures.

![Figure 7](image_url)

**Figure 7.** (a) TG–differential thermal analysis of residual coal after combustion under 4 MPa and (b) remaining combustion and (c) TG inflection curve.
cracks. The cracks affect the heat transfer process and oxygen supply. The opening of the channel provides favorable conditions.

2.3. Thermogravimetric Analysis of Residual Coal. To further explore the influence of each axial pressure condition on the briquette oxidation process, the STA449C synchronous thermal analyzer was used to measure the residual briquette after burning under different axial pressure conditions. Comparing the change in thermal weight loss (Figure 7a) and the final residual mass percentage (Figure 7b) under each axial pressure from 30 to 400 °C, the TG curve (Figure 7) is obtained, and the special inflection points of each curve are found, as shown in Table 3.

### Table 3. Inflection Point Value of the TG Curve of the Residual Coal Sample

| axial compression/MPa | minimum weight temperature (°C) | minimum weight ratio (%) | maximum weight temperature (°C) | maximum weight ratio (%) |
|-----------------------|---------------------------------|-------------------------|---------------------------------|-------------------------|
| 0                     | 113.4                           | 99.99952                | 300.9                           | 102.00                  |
| 2                     | 140.7                           | 99.70028                | 283.2                           | 100.59                  |
| 4                     | 160.0                           | 99.2873                 | 282.5                           | 100.49                  |
| 6                     | 132.1                           | 99.59417                | 287.1                           | 101.11                  |

The spontaneous coal combustion process is the combined action of physical and chemical adsorption and a chemical reaction. When the coal temperature reaches 30–50 °C, physical adsorption and the reaction become the dominant factors to promote the spontaneous combustion of coal. The thermal weightlessness image is shown in Figure 7a. It can be seen that the period from the beginning of oxidation to the maximum weight loss point belongs to the stage of gas desorption and water evaporation. Then, because of chemical adsorption, mass growth occurs, and the maximum weight gain is reached. Finally, a rapid decline in quality occurs during the gradual approach to the ignition point until combustion. From the curve in Figure 7c, it can be seen that the overall TG of 4 MPa residual coal is smaller than that of other treated coal samples. The maximum oxidation weight loss is obviously smaller than the rest of the axial pressure. The main reason is that the coal sample stimulates more organic active molecules during the first oxidation under 4 MPa axial pressure. After the temperature is raised again, the active molecules quickly participate in the coal–oxygen reaction, which causes a relatively large reduction in mass. From the inflection point value of the experimental coal samples in Table 3, when the axial pressure is 4 MPa, the maximum mass loss rate of residual coal occurs at 160 °C, while the temperature of the residual coal under the other axial pressures is lower than that at 4 MPa. The temperature at 4 MPa is 46.6 °C higher than that at 0 MPa, which shows that during the process of applying axial pressure oxidation, the coal sample at 4 MPa needs a higher temperature to reach the maximum mass loss rate and the minimum weight value is less than that of the other treated coal samples. This is mainly because the initial oxidation at 4 MPa is more oxidized than at other axial pressures, the coal–oxygen reaction is more intense, and the coal–oxygen reaction process is higher when the oxidation stops. In the process of oxygen absorption and weight gain, the temperature corresponding to the maximum weight point of the 4 MPa oxidized residual coal sample is lower and compared with that at 0 MPa, it is reduced by 18.4 °C. The mass growth rate is also relatively low. This result further shows that the excessively fast oxidation process in the 4 MPa axial pressure oxidation test makes the amount of coal-like combustible inorganics decrease, and the chemical adsorption amount decreases when it is oxidized again. In the final stage of thermogravimetric oxidation (greater than 500 °C) shown in Figure 7b, as the axial pressure increases, the weight residual rate decreases and then increases. The 4 MPa thermogravimetric residual rate is larger mainly because in the process of axial pressure oxidation, the amount of inorganic matter burned in coal is relatively large, which reduces the reburnable organic matter in coal. Therefore, it is indirectly proven that the reaction is more violent in the ACTP system when the axial pressure is 4 MPa, and the spontaneous combustion process of the coal–oxygen composite reaction is faster.

Figure 8 shows the DSC experimental results for 4 MPa residual coal. There were two thermal stages in the DSC curves. According to endothermic and exothermic processes, three stages of the residual coal oxidation process under four axial pressure conditions are defined, and the characteristic temperature points are found, as shown in Table 4. The first stage is the partial residual coal gas desorption process, which is mainly manifested as a low-temperature oxidation endotherm, according to the intensity of the axial pressure.

Figure 8. DSC curve of residual coal combustion.
applied in the first oxidation and showing the change in the temperature at the beginning and the end. When the axial pressure is 0 MPa, because the structural characteristics of coal are not destroyed during the oxidation stage of the ACTP system, the sensitivity to temperature is low when it is oxidized again, and there is no oxidation endothermic phenomenon. When the axial pressures are 2, 4, and 6 MPa, the endothermic temperature range first decreases and then increases. The minimum endothermic temperature span at 4 MPa is only 8.7 °C. The second stage (including TD1 and TD2) is the accelerated oxidation combustion stage. This stage is characterized by an increase in the amount of heat released and an increase in the amount of oxygen absorbed, and there are two exothermic peaks. Although the axial pressure increases, the maximum heat release temperature (TD3) decreases, and the corresponding maximum heat release has a trend of first decreasing, then increasing, and finally decreasing. The maximum amount of heat released from residual coal with an axial pressure of 4 MPa reaches the maximum. At 17.6 mW mg⁻¹, the peak temperature (TD3) at which the heat release rate is reached again is relatively low (440 °C). As the axial pressure increases, the total amount of heat released first decreases and then increases. Except for 0 MPa, the total heat release of the residual coal under the axial pressure of 4 MPa is greater, which shows that more heat accumulates in the oxidation process and that there is a higher tendency for spontaneous combustion. In addition, it can be seen from Table 4 that the temperature at which coal reaches burnout is the lowest at 4 MPa (575 °C), indicating that coal burned more completely during the application of axial pressure. During the process of measuring the amount of heat released by oxidation again, there is less residual combustion. On the whole, the process of applying different axial pressures to increase the temperature of the sample changes the exothermic characteristics of coal sample recombustion. The overall heat release of the residual coal with a shaft pressure of 4 MPa is higher, and the temperature corresponding to the maximum heat release is reached earlier. Compared with the other axial pressures, the maximum heat release is higher at 4 MPa. The reason for the DSC change may be that during the initial axial pressure oxidation, the internal macromolecular group burned and ruptured, and the oxidation process at different axial pressures altered the side groups on the molecular chain, making them loose and be in an irregular state. Although the difference is slightly eliminated after the temperature is lowered, the combustion of coal is an irreversible process, including the relative mass of coal molecules and the degree of branch-chain destruction. Changes in the ease and amount of heat released by recombustion reflect the process difference of the first oxidation combustion mechanism under different axial pressures.

### 3. CONCLUSIONS

1. By analyzing the oxidation process of briquettes under different axial pressures, it can be seen that at an axial pressure of 4 MPa, the oxidation heating rate is higher, the crossing point temperature is reached earlier (86.92 °C), the oxygen consumption rate is faster, and the apparent activation energy is the smallest in the two stages (the second stage is 8.77 kJ/mol). Combined with the fitted oxygen consumption rate curve, the application of an axial pressure of approximately 4 MPa can promote the oxidation reaction to a certain extent.

2. Changes in the pore structure and heat transfer characteristics of briquettes under different axial pressures are obtained. It can be seen that when the axial pressure is 4 MPa, the average porosity begins to increase and the inorganic mineral molecules rupture from the axial pressure, providing a large number of channels for oxygen movement, enhanced thermal conductivity, and accelerated oxidation and combustion.

3. The maximum mass loss rate and maximum mass growth rate of residual coal after combustion under 4 MPa shaft pressure are lower (99.2873 and 100.49%, respectively). The former is slightly delayed in reaching this temperature, and the latter is slightly accelerated in reaching this temperature; the residual coal weight under a shaft pressure of 4 MPa after combustion is higher (13.6%), which indicates that it is burned completely under this shaft pressure and that the combustible amount of reoxidation combustion is relatively small. Except for the case when no axial pressure is applied, the total heat release is higher when the axial pressure of 4 MPa is applied again.

4. Axial pressure changes affect the occurrence of spontaneous coal combustion. The mining site should avoid changes in axial pressure of approximately 4 MPa in the coalfield-fire area. By simulating the oxidative combustion characteristics of briquettes constructed under different stress conditions on site, theoretical guidance can be provided for the prevention and control of spontaneous coal combustion disasters caused by the combined action of stress fields and temperature fields in coalfield-fire areas.

### 4. EXPERIMENTS AND METHODS

#### 4.1. Samples

The coal samples used in this study came from a coal mine in Xinjiang; it belongs to the category of bituminous coal. The coal sample had the characteristics of minimal weathering, a low ignition point, minimal spontaneous combustion during stacking, intermediate heat generation, and so forth. This coal sample was used in this experiment, which can show well the oxidative combustion characteristics of the coalfield-fire area. A large piece of coal was selected from the working face of the 2-1 coal seam underground and was wrapped tightly with nylon bags and shipped back to the laboratory. The results of industrial and elemental analyses of the coal are shown in Table 5. After the coal sample was crushed, sieved smaller than 0.1 mm, and pressed into a hydraulic device and handmade mold, the specifications were
100 mm column height and 50 mm radius. The samples were perforated at the center $T_1$, distance $T_2 = 20.6$ mm and center $T_3 = 36.2$ mm, which was used to place temperature probes. The processed coal samples were placed in a vacuum-drying cabinet for 72 h, dried, and then placed in sealed bags for later use.

4.2. Experimental System. The ACTP system (Figure 9) consists of a programmed temperature (TP) oven, heating device, insulating layer, gas path, piston, cylindrical container (100 mm in diameter and 150 mm in height), and three temperature sensors with an accuracy of 0.1 °C. The inlet air was heated to the same temperature with the oven. Gaseous products (such as CO, CO$_2$, CH$_4$, C$_2$H$_2$, C$_2$H$_4$, and O$_2$) from the coal samples were separately analyzed by gas chromatography with an accuracy of 10$^{-4}$ ppm. The temperatures at three measuring points (Figure 9) in the oven were collected and obtained every 20 s.

The experimental procedure was as follows: the coal pillar was removed and slowly placed in the test furnace; the cover was tightened, and the dry air was checked to ensure the air tightness of the test system; the experimental gas supply flow rate was 1200 mL/min; the following parameters were set: furnace program heating rate: 10 °C/min; heating range: 30–450 °C; temperature data collection cycle: 20 s; and gas data collection starting temperature: 40 °C. After the parameters were set, the ACTP system was opened to start the experiment. When the measurement point $T_1$ reached 30 °C, 0, 2, 4, and 6 MPa axial pressure experiments were conducted, and gas chromatography was used to measure the released gas when the measurement point $T_1$ reached 40 °C. The gas was collected once every 12 min during the heating process, and the fixed axial pressure was manually maintained during the experiment.

The coal sample at the burning coal pillar $T_1$ in Figure 9 was used for thermal analysis on a STA449C synchronous thermal analyzer (made by NETZSCH in Germany). The initial temperature was set at 30 °C, the heating rate was 10 °C/min, the termination temperature was 800 °C, the coal sample mass under different axial pressures was 25 ± 1 mg, and the sample container was Al$_2$O$_3$. Set protective gas 1 (N$_2$) flow rate: 20 mL/min; purge gas 1 (N$_2$) flow rate: 20 mL/min; and purge gas 2 (O$_2$) flow rate: 10 mL/min. Experiments were carried out under nitrogen and oxygen to obtain thermal weight loss and heat release curves.

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### Table 5. Proximate and Ultimate Analyses for the Experimental Coal/%

|          | M$_{ad}$ | A$_d$  | V$_{daf}$ | FC$_{daf}$ | C$_{daf}$ | H$_{daf}$ | N$_{daf}$ |
|----------|---------|-------|---------|-----------|---------|---------|---------|
|          | 6.55    | 8.86  | 37.15   | 57.29     | 70.86   | 5.44    | 0.69     |

Figure 9. Coal spontaneous combustion characteristic parameter test device and experimental coal sample map under various conditions.
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Notes
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