

Original Paper

Large-scale 3D experimental study on in-situ pyrolysis of tar-rich coal (I): Heat transfer behavior and product characteristics under conductive heating



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ARTICLE INFO

Article history:

Received 26 August 2025

Received in revised form

9 January 2026

Accepted 2 April 2026

Available online 7 April 2026

Edited by Xi Zhang

Keywords:

Tar-rich coal

Conductive heating

In-situ pyrolysis

Pore blockage

Ordos Basin

ABSTRACT

Conductive heating is a key method for in-situ pyrolysis of tar-rich coal. However, the temperature and pressure characteristics, oil and gas production mechanisms, and reaction zone characteristics under high-pressure, large-scale conditions remain poorly understood. This study focuses on tar-rich coal from the eastern Ordos Basin in China and develops an experimental apparatus for in-situ high-temperature, high-pressure pyrolysis. Conductive heating experiments were performed, and the temperature, pressure, and oil and gas products were analyzed. CT scanning, Rock-Eval pyrolysis, and XRD analysis were also conducted on the post-pyrolysis rock samples. The results show that due to the low thermal conductivity of tar-rich coal, the heat injection capacity is inadequate, with the heater power efficiency reaching only 1.73%. After 482 h of experiment, the oil recovery is 1.97%, and the gas recovery is 27.86%. The oil consists of light components, and the gas primarily consists of CH₄. Because the temperature near the production well remains low, pyrolysis products migrating there cause heavy components to condense and accumulate, reducing local porosity to 0.25%. Furthermore, gaseous and light pyrolysis products preferentially migrated upward and accumulated near the top of the physical model. Therefore, arranging the production wells above the heating wells is recommended. This study offers theoretical support and experimental evidence for the in-situ pyrolysis of tar-rich coal using conductive heating.

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1. Introduction

Coal is a significant component of the global energy system. Tar-rich coal is defined as coal with an oil yield ranging from 7.0% to 12.0% in the Gray-King assay. It is rich in hydrogen-rich structures capable of producing oil and gas, functioning as an integrated

coal-based oil and gas resource. Tar-rich coal is abundant, and its utilization methods primarily include surface pyrolysis and in-situ pyrolysis. Although the surface pyrolysis process is well-established, it is costly, environmentally damaging, and technically limited, hindering large-scale application (Guo et al., 2025; Ju et al., 2021). In contrast, in-situ pyrolysis has emerged as a research hotspot due to its low cost, minimal land use, and environmental benefits (Kelly et al., 2016). The key issue in in-situ pyrolysis of tar-rich coal is achieving rapid heating of the coal seam and efficient pyrolysis. Based on the heating method, in-situ pyrolysis can be categorized into conduction (Fowler and Vinegar, 2009), convection (Guo et al., 2024; Kang et al., 2020, 2023), radiation (Wang et al., 2022), and reaction heat heating (Guo et al.,

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Peer review under the responsibility of China University of Petroleum (Beijing).

2023a). Conduction heating transfers heat to the coal seam via the heater, heating the tar-rich coal seam by thermal conduction. This technology is easy to operate, avoids combustion, reduces harmful gas emissions, and provides significant environmental benefits. Shell's in-situ conversion process (ICP) is a representative example of conductive heating technology applied in oil shale formations, and its feasibility was confirmed through seven field tests conducted in Colorado, USA (Shen, 2019).

Researchers have recently focused on temperature, pressure, oil and gas generation mechanisms, and reaction zones of tar-rich coal during conductive heating in laboratory experiments. The results show that increasing the temperature typically enhances the conversion rate of tar-rich coal (Xu et al., 2019; Yuan et al., 2012). The pyrolysis temperature of tar-rich coal is primarily between 400 and 550 °C, and the pyrolysis reaction is generally divided into three stages: release of moisture and adsorbed gases, production of a large amount of tar and gaseous hydrocarbons, and coking polycondensation with secondary cracking (Ma et al., 2022). As the pyrolysis temperature increases, the gas yield gradually rises, the alkane content in the tar decreases, and the content of aromatics and phenols increases. When pyrolysis temperatures exceed 450 °C, tar typically undergoes secondary cracking (Kelly et al., 2016). The primary factors affecting temperature are thermal physical parameters (Xue et al., 2022), including thermal diffusivity, specific heat capacity, thermal conductivity, density (Zhu et al., 2022), and heating rate (Xu et al., 2019). As temperature increases, the thermal diffusivity of tar-rich coal typically decreases, while its specific heat capacity and thermal conductivity tend to increase. These changes affect the thermal conductivity and pyrolysis reaction time of the coal seam. The density of tar-rich coal directly affects the thermal conductivity. Higher density typically leads to lower thermal conductivity, reducing heat transfer (Chen et al., 2021). Moreover, as the heating rate increases, the decomposition temperature of tar-rich coal shifts toward higher temperatures (Strezov et al., 2004). Pressure is a significant factor influencing the in-situ pyrolysis of tar-rich coal (Suo et al., 2024a, 2024b). Primarily regulated by temperature variations, pressure has a lesser impact on pyrolysis product yield than temperature (Tian et al., 2025). Pressure affects both heat and mass transfer within the coal seam. As pressure increases, the yield of volatile matter significantly decreases, the tar conversion rate drops, the retention time of tar in the coal increases, and the secondary cracking of tar, along with radical polycondensation of coke, is intensified, leading to an increase in coke yield (Tremel et al., 2012; Zhang et al., 2024). The pyrolysis reaction zone of tar-rich coal is governed by the coupled effects of temperature, pressure, and material migration (Qiu et al., 2023; Wang et al., 2024). The generation and migration constraints of pyrolysis fluids affect the output pattern of pyrolysis products (Çakal et al., 2007). As the pyrolysis temperature increases, the pore properties of the coal sample undergo significant changes, with macropores consistently occupying most of the pores, while micropores initially increase and then decrease (Shi et al., 2023). Furthermore, increases in pore diameter and the pore-throat ratio enhance connectivity, further improving the efficiency of the pyrolysis reaction (Wang et al., 2023). Observing the apparent structure of coke after pyrolysis indicates that as the pyrolysis temperature rises, the changes in porosity become more stable. Above 700 °C, the inorganic mineral CaO can still be detected (Che et al., 2023). Stress also affects the connectivity of coal. In low-stress environments, coal exhibits higher porosity, which promotes the efficient migration of tar and gas components (Shi et al., 2024).

Significant progress has been made in laboratory experiments on the conductive heating of tar-rich coal, providing essential

foundational data and theoretical support for studying its pyrolysis characteristics. Previous studies have primarily focused on the direct impacts of temperature and pressure on the in-situ pyrolysis of tar-rich coal, with comparatively less emphasis on the dynamic evolution of the pyrolysis process. Meanwhile, research on oil and gas products has mainly focused on their generation mechanisms, with relatively limited studies on the synergistic mechanisms during generation and migration. Research on the reaction zone has primarily focused on pore structure and apparent structure, with little attention to the impact of organic matter and inorganic minerals on pore structure during pyrolysis. It is crucial to note that in-situ pyrolysis of tar-rich coal typically occurs under high-pressure, large-scale, and complex conditions. The process involves the dynamic evolution of temperature and pressure, the generation and migration of oil and gas, and the opening and closing of pores and fractures, all of which are coupled with various factors (Zhu et al., 2021). Current research on the temperature and pressure characteristics, oil and gas production mechanisms, and reaction zone characteristics during high-pressure, large-scale conductive heating of in-situ pyrolysis of tar-rich coal lacks sufficient systematization and depth.

This study focuses on tar-rich coal from the eastern Ordos Basin in China and develops an experimental apparatus for in-situ high-temperature, high-pressure pyrolysis. This apparatus conducted conductive-heating experiments to study the temperature and pressure characteristics, oil and gas generation mechanisms, and reaction-zone characteristics during the in-situ conversion process. This study recorded temperature and pressure data during pyrolysis, collected oil and gas products, and analyzed them using gas chromatography and mass spectrometry. The pyrolyzed rock samples were simultaneously subjected to multidimensional characterization, including XRD analysis and Rock-Eval pyrolysis experiments to determine the composition and transformation properties of organic matter and inorganic minerals, and CT scanning to evaluate changes in pore structure. Furthermore, the heater power was evaluated. This work provides the experimental foundation and theoretical support for the in-situ pyrolysis of tar-rich coal under conductive heating conditions.

2. Materials and methods

2.1. Materials

The tar-rich coal samples used in this study were collected from the eastern Ordos Basin, China (Wang et al., 2019), as shown in Fig. 1. The coal seam has a burial depth of 1500 m and a thickness of 12.96 m. The basic physicochemical properties of the raw tar-rich coal are shown in Table 1. The tar and gas yields were determined using a Fischer assay apparatus. The pyrolysis was carried out at 550 °C with a heating rate of 10 °C/min under a nitrogen atmosphere. The sample was held for 2 h at the target temperature. Under these conditions, the tar yield was 9.11%, and the gas yield was 5.75%. The S1 value of 8.29 mg/g indicates a relatively high abundance of free hydrocarbons. The S1 value of 8.29 mg/g indicates a relatively high abundance of free hydrocarbons. The pyrolytic hydrocarbon S2 value is 119.72 mg/g, indicating significant hydrocarbon generation potential. The inorganic minerals consist mainly of kaolinite and tobelite, with small amounts of calcite and pyrite; the maceral composition is primarily composed of vitrinite and inertinite.

2.2. Experimental apparatus and procedure of in situ pyrolysis

This study conducted in situ conductive pyrolysis experiments on tar-rich coal using a self-developed experimental apparatus.

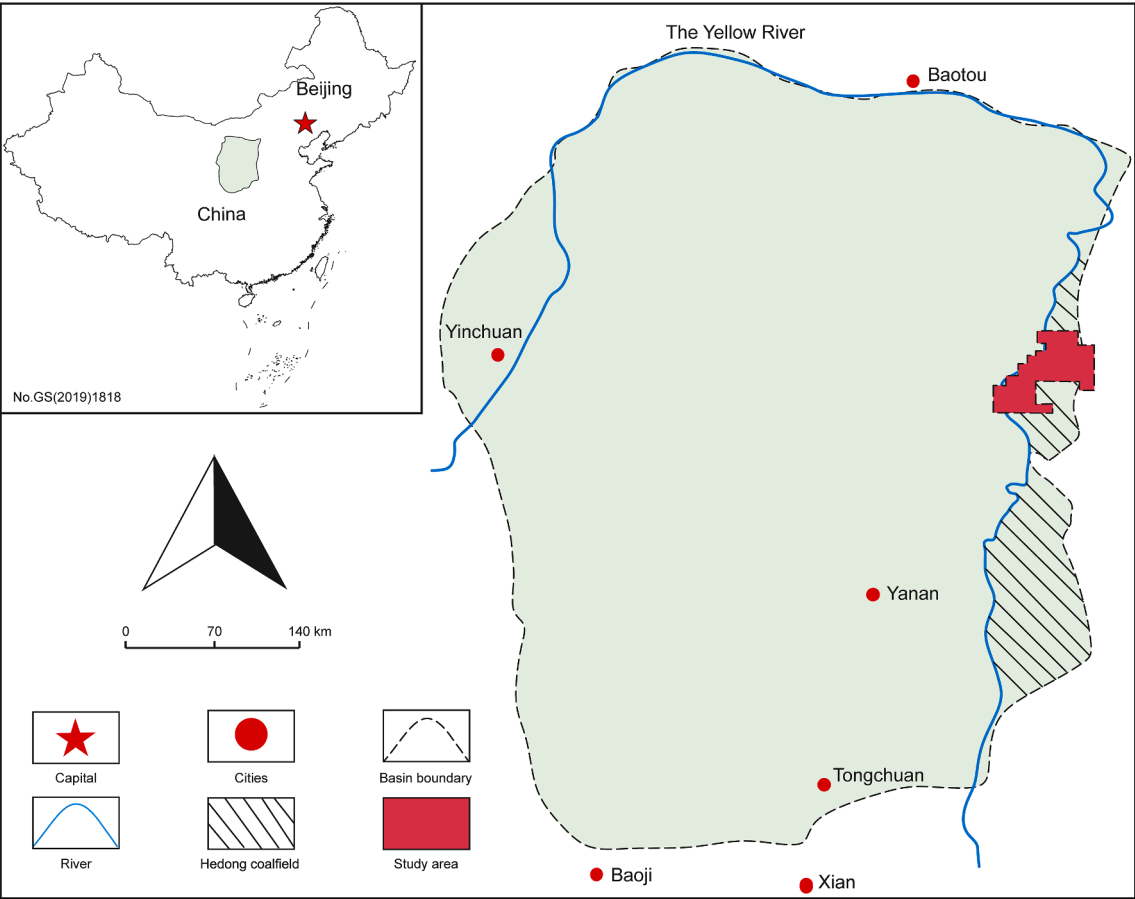


Fig. 1. Geologic map of the sample region.

Table 1
Basic physicochemical properties of the tar-rich coal.

Fischer assay analysis (ad, wt %)		Rock-Eval		Inorganic minerals, %		Maceral and mineral composition, %	
Tar	9.11	S1, mg/g	8.29	Kaolinite	69.58	Vitrinite	47.8
Gas	5.75	S2, mg/g	119.72	Calcite	9.1	Inertinite	48
Water	3.03	-	-	Pyrite	1.21	Liptinite	0.6
Char	82.11	-	-	Tobelite	20.11	Mineral Matter	3.6

Fig. 2 shows the in-situ pyrolysis experimental apparatus for tar-rich coal, which consists of four main parts: the injection system, the high-temperature and high-pressure reaction system, the product collection and measurement system, and the data collection and control system.

Fig. 3 shows the high-temperature, high-pressure reactor. The reactor has an inner diameter of 710 mm, a height of 1000 mm, and a 400 mm support assembly at the bottom. Four oil outlets are located at the bottom of the reactor, positioned 250 mm from the center. The interior structure of the reactor includes a heater, heating tubes, and a central tube, arranged as follows: the tops of the heating tubes are 100 mm above the bottom of the reactor, and the top of the heater is 200 mm above the bottom of the reactor. To monitor the reaction process in real time, At each radial distance of 125, 250, and 320 mm, four stainless-steel tubes were installed, with five temperature sensors arranged along each tube, giving 60 sensors in total. Temperature sensor probes are mounted at 100 mm, 300 mm, 500 mm, 700 mm, and 900 mm above the bottom of the reactor. Five tracking heaters are assembled outside

the reactor to prevent heat loss. The reactor is wrapped with a layer of asbestos-mesh insulation to further minimize heat loss. The top of the reactor has six pressure sensors to monitor one inlet, one experimental, and four outlet pressures. This study will analyze the reactor using its half-sectional view, focusing on analyzing the highlighted red area, as shown in Fig. 3(c).

The experimental procedure consists of three stages: (1) core preparation, (2) equipment assembly, and (3) data collection, as shown in Fig. 4. The core preparation procedure is as follows: First, the block samples are crushed into powder with a particle size finer than 120 mesh. The core samples are manufactured using a segmental pressing method. A 10 kg sample of 120-mesh tar-rich coal is poured into the reactor, and the pressure is maintained at 40 MPa for 10 min to ensure the uniformity of the core sample. This process is repeated until a cylindrical core with a 710 mm diameter and a 1000 mm height is formed. This preparation method is considered appropriate and widely accepted in similar studies (Xu et al., 2023; Yang et al., 2023). The apparatus assembly phase includes assembling the reactor lid, heating tubes, heaters,

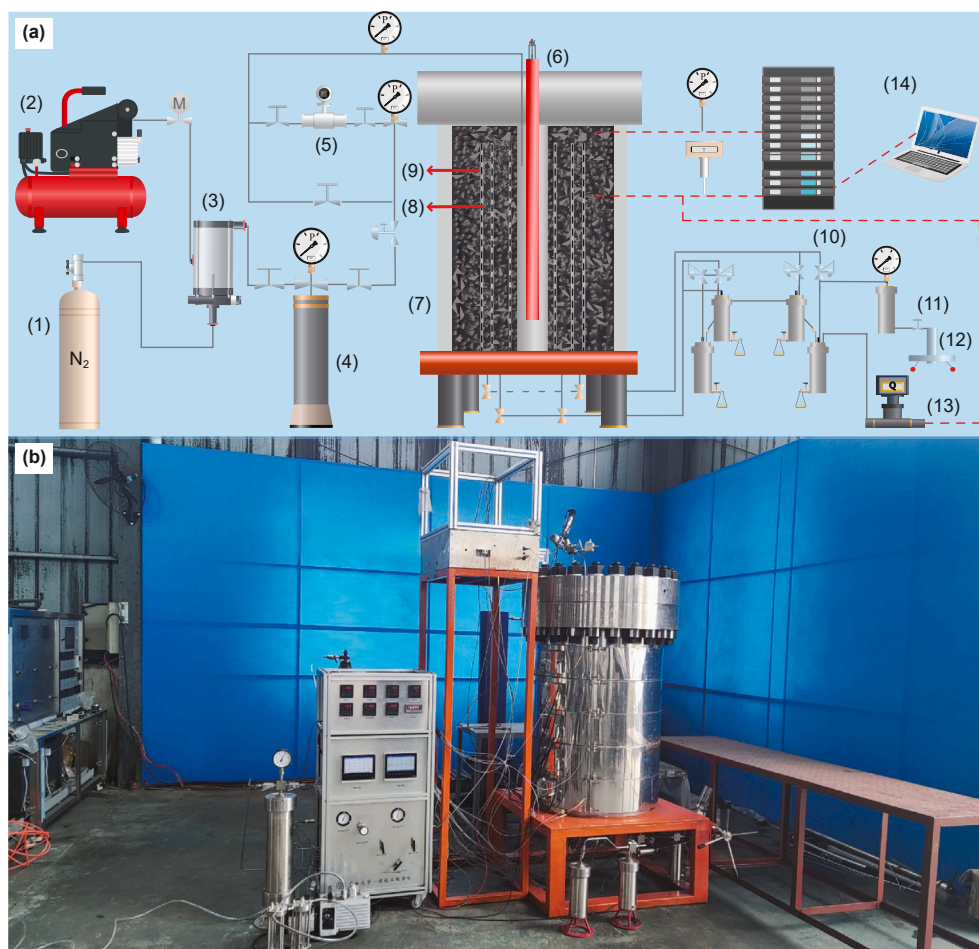


Fig. 2. The in-situ pyrolysis experimental apparatus for tar-rich coal. (a) Schematic diagram; (b) experimental apparatus. (1) gas cylinder, (2) air compressor, (3) booster pump, (4) buffer tank, (5) gas flow meter, (6) heater, (7) reactor, (8) coal sample, (9) temperature sensor, (10) back pressure valve, (11) product collection tank, (12) hand pump, (13) gas flow meter, (14) data acquisition.

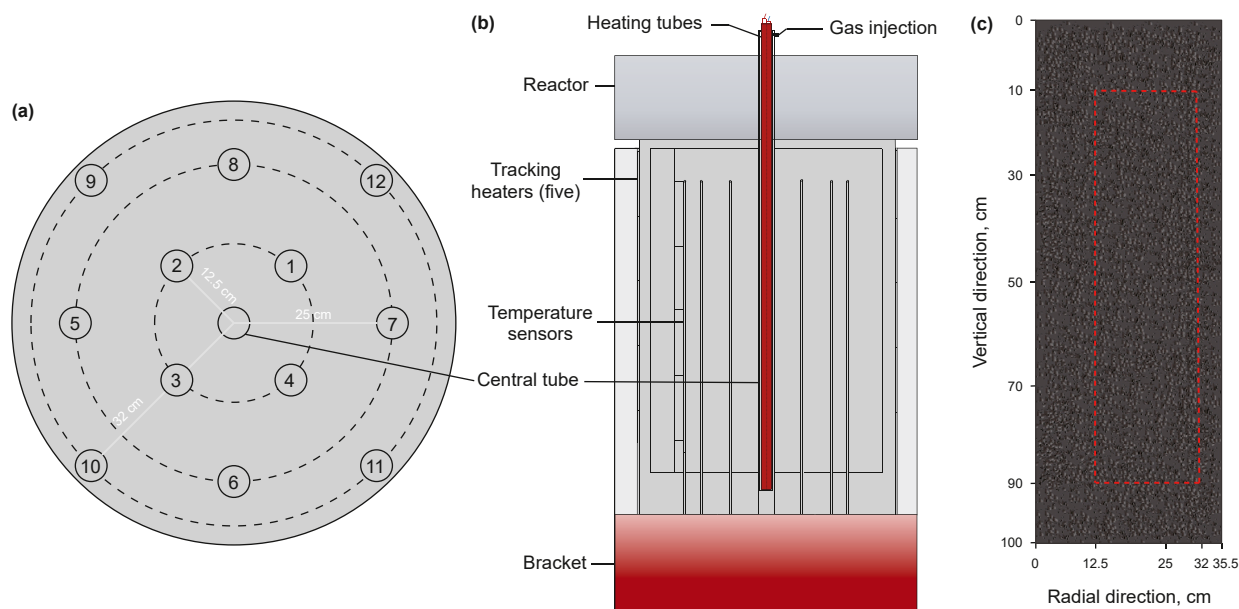


Fig. 3. The high-temperature and high-pressure reactor. (a) Top view, (b) front view, (c) half-sectional view.

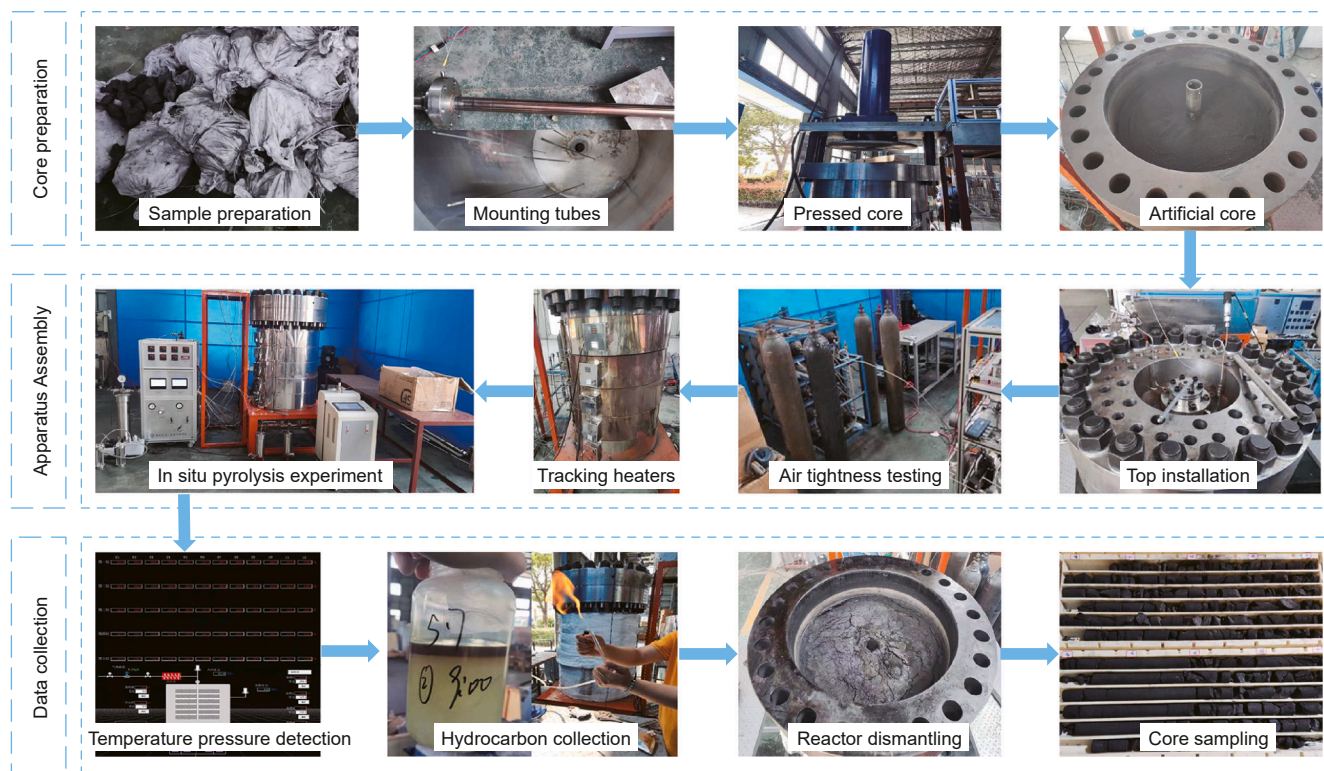


Fig. 4. Tar-rich coal in-situ pyrolysis experimental procedure.

tracking heaters, 60 temperature sensors, and pressure sensors. After assembly, threaded sealing is performed, followed by leak and pressure testing of the apparatus. The core sample is then tested in its original state, with an initial permeability of 2.36 mD. At this point, all preparations have been completed. During the data collection phase, the heating power of the heater is set to 3 kW/m, and the heater temperature is set to 500 °C to initiate the experiment. Temperature data from 60 sensors and data on the heater temperature, inlet pressure, outlet pressure, and reactor pressure will be collected in real-time. Additionally, oil and gas products from the reactor outlet will be collected every 3 to 8 h until no more pyrolysis products are generated. At this point, the experiment will be stopped. After the experiment, the reactor will be disassembled, and core samples will be collected for analysis.

2.3. Analytical methods

The tar components were analyzed using an Agilent 7890A gas chromatograph and an Agilent 5975N mass spectrometer. The injection port temperature was maintained at 300 °C with a split ratio of 50:1. The analysis was performed with CH_2Cl_2 as the solvent and a solvent delay time of 4 min. The interface temperature of the gas chromatograph and mass spectrometer was maintained at 280 °C, the quadrupole temperature at 150 °C, the ion source temperature at 230 °C, and the ionization voltage at 70 eV. Data were collected using the Agilent MSD ChemStation and analyzed with Agilent software (NIST 2.0).

The gas components were analyzed using an Agilent 7890B gas chromatograph equipped with a flame ionization detector (FID) and two thermal conductivity detectors (TCD1 and TCD2). The analysis employed an HP-AL/S chromatographic column, with FID for detecting hydrocarbon gases ($\text{C}_1\text{--C}_6$), TCD1 for CO_2 , H_2S , O_2 , N_2 , and CO , and TCD2 for hydrogen (H_2). Data collection and analysis

were conducted using Agilent Open Lab software. Nitrogen, considered an inert gas, was excluded from the analysis of relative percentages.

The organic parameter analysis of the coke was conducted using an OG-2000VA Rock-Eval pyrolysis instrument. The sample particle size was less than 200 mesh, with 10 mg used for each test. Blank and standard samples were tested before the sample analysis, and each was tested three times under the same conditions. FID was used to detect peaks including S_0 , S_1 , S_2 , and T_{max} . The residual organic matter after pyrolysis was oxidized to CO_2 and then catalytically hydrogenated to form CH_4 , which was quantitatively detected by FID to obtain S_4 . The total organic carbon content of the sample was calculated. This method enables the rapid evaluation of oil generation potential, maturity, organic matter, and the properties of reservoir rocks.

The mineral composition and content were determined using the X'Pert Pro X-ray diffractometer (PANalytical, Netherlands). The X-ray tube employed a copper target with a maximum voltage of 60 kV, a current of 55 mA, and an output power of 3 kW. The sample was positioned horizontally, with a 2θ angle range from 1° to 160°. The sample position remained fixed during the test, while the X-ray tube and detector rotated around it. The instrument was equipped with the PDF-2 International Powder Diffraction Database, enabling qualitative and quantitative phase analysis. Different minerals exhibit unique diffraction patterns during the analysis. The relative mineral content can be determined based on the intensity of the diffraction peaks.

The pore structure of the coke was analyzed using the Nano Voxel 5000 high-resolution X-ray 3D microscope, operating at the micro-nano scale (Zhu et al., 2025). The instrument is equipped with a dual X-ray source system (20–160 kV/20–240 kV), providing a maximum power of 25W/350W, a spatial resolution of 500 nm, a

pixel resolution of 200 nm, and a maximum sample size of 600 mm in both diameter and height. The flat-panel detector has an image area of 427 mm × 427 mm and a pixel matrix of 3072 × 3072. The instrument offers various scanning modes, including helical, biased, and limited-angle scanning, and exhibits strong expandability. After data collection, modeling and analysis are performed using Avizo software.

3. Results and discussion

3.1. Temperature and pressure characteristics

3.1.1. Temperature and pressure evolution characteristics

Fig. 5 shows the temperature variation curves during conductive heating. As shown in Fig. 5(a), at 12.5 cm in the near-source zone, 0–160 h corresponds to a rapid heating stage with an average heating rate of 1.49 °C/h. The temperature increase is most pronounced at the mid-level heights of 50 cm and 70 cm, reaching first-stage peak temperatures of 317.18 °C and 308.45 °C at 160 h, respectively. During this stage, volatile components begin to be released slowly. Following the heater failure at 160 h, the temperature field is noticeably perturbed. From 160 to 342 h, the system enters a slow heating stage, and the average heating rate decreases to 1.40 °C/h with continuous release of pyrolysis products; notably, at 261 h the temperature at the location corresponding to 30 cm reaches a peak of 484.2 °C and then declines, and the post-peak cooling may be associated with the endothermic effect of tar-rich coal pyrolysis. The heater failed again at 342 h; 342–482 h constitutes a stable stage in which the average heating rate drops to 0.57 °C/h and the temperature variation becomes slower, indicating that the conductive heat-transfer process gradually approaches equilibrium; the overall average heating rate at 12.5 cm over the entire period is 0.72 °C/h. As shown in Fig. 5(b), at 25 cm, the heating rates in all stages are clearly lower than those at 12.5 cm. The average heating rates for the three stages are 1.11 °C/h, 1.23 °C/h, and 0.47 °C/h, respectively. In particular, at 309 h the peak temperature at the position corresponding to 30 cm reaches 455.43 °C, and after 398 h the temperature remains essentially at 340 °C with the temperature rise tending to stagnate; the overall average heating rate at 25 cm is 0.68 °C/h. As shown in Fig. 5(c), at 32 cm, the temperature rise is further constrained. The average heating rates for the three stages are 1.02 °C/h, 0.97 °C/h, and 0.56 °C/h, respectively. After 424 h, the temperature remains essentially stable at 348 °C, indicating that heat transfer at this radius has significantly attenuated and reached a steady state. The overall average heating rate at 32 cm over the entire period is 0.68 °C/h. Overall, the conductive-heating process exhibits a relatively slow heating rate that gradually decreases over time, with an average heating rate of 0.70 °C/h. Heat transfer is faster near the heat source, and temperature fluctuations are more pronounced. With increasing radial distance, both the heating rate and peak temperature decrease significantly, indicating substantial attenuation of heat during long-distance propagation.

Fig. 6 shows the pressure variation curves during conductive heating. During 0–160 h, the inlet pressure is generally slightly higher than the outlet pressure, with an average pressure difference of approximately 0.02–0.03 MPa. At this stage, volatile matter in the tar-rich coal is gradually liberated, the product throughput is low, and pressure variations are insignificant. During 160–342 h, as a large amount of liquid products precipitates, the pressure differential increases markedly. Around 321 h, the inlet pressure continues to rise while the outlet pressure drops to 0.03 MPa; the maximum pressure differential reaches 16.03 MPa, resulting in blockage. This may be related to polycondensation reactions in the

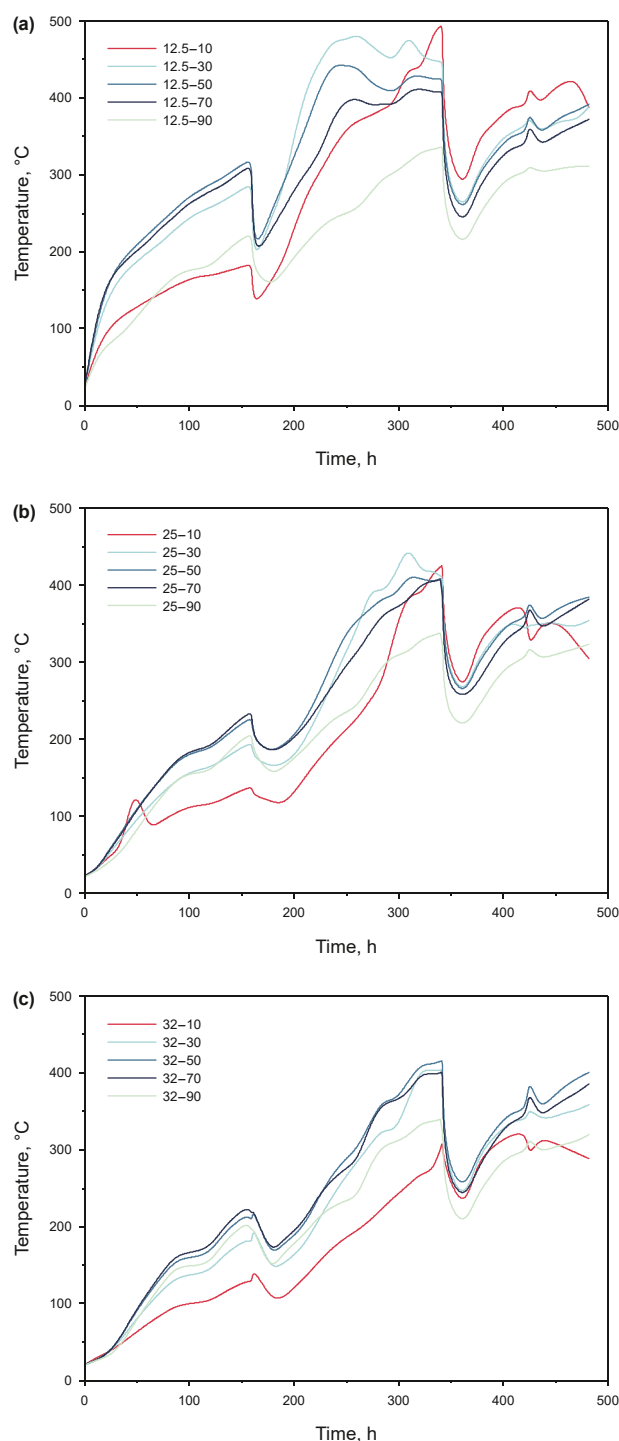


Fig. 5. The temperature variation curves during conductive heating: (a) 12.5 cm, (b) 25 cm, (c) 32 cm.

low-temperature zone and the accumulation of heavy components (Guo et al., 2022). During 342–482 h, the pressure still shows some fluctuations, but after 446 h, the internal pressure of the sample tends to stabilize. Overall, during conductive heating, the pressure gradually fluctuates due to the generation and migration of volatile products. For most of the time, gas generation and release are relatively stable, with an average pressure differential of about 0.18 MPa. Abnormal changes occur only when heater failures or blockages take place.

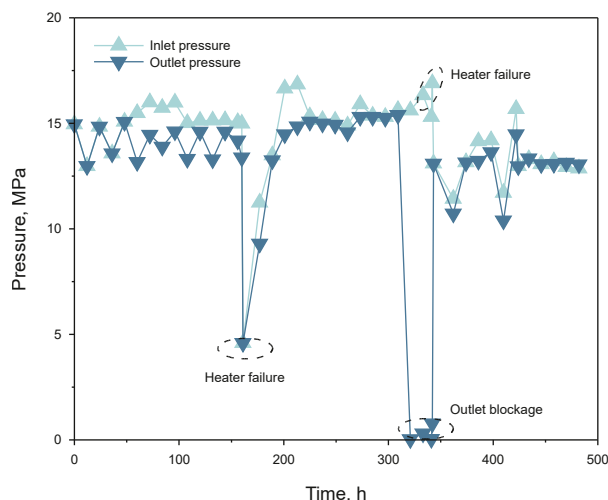


Fig. 6. The pressure variation curves during conductive heating.

Fig. 7 shows the map of the temperature field variation. At 160 h, the temperature at the center exceeded 260 °C, reaching a maximum of 317.18 °C, while the temperature at the top edge was the lowest at 128.3 °C, and heat transfer primarily occurred within the tar-rich coal layer. At 249 h, the 12.5–30 zone temperature exceeded 474 °C, and temperatures in most areas exceeded 308 °C. The tar-rich coal began pyrolysis. At 342 h, the 12.5–10 zone temperature reached 492.1 °C, with heat conduction upward. In most other zones, the temperature exceeds 404 °C. At 424 h, the temperature slightly decreased, but it remained above 356 °C near the center. The tar-rich coal continues pyrolysis at 482 h, and the temperature in the central zone slightly increases, possibly due to the exothermic coke polycondensation reaction (Wang et al., 2020). During conductive heating, the temperature is concentrated in the central zone and gradually transferred radially and upward. The temperature transfer was slow and significantly attenuated, forming a distinct temperature gradient with a maximum difference exceeding 280 °C.

3.1.2. Heater power

Once the heater reaches the rated temperature, the system automatically switches to an isothermal holding mode. To analyze this physical process, this study employs the unsteady heat conduction model for a semi-infinite solid with the first-type boundary condition (constant temperature). For a semi-infinite solid, the instantaneous heat flux $q(x, t)$ at a distance x from the heating surface at any time t can be expressed as:

$$q(x, t) = k \frac{(T_w - T_0)}{\sqrt{\pi \alpha t}} \exp\left(-\frac{x^2}{4\alpha t}\right) \quad (1)$$

Where $q(x, t)$ is the heat-flux density, W/m²; T_w is the heater surface temperature, °C; T_0 is the initial temperature of the coal sample, °C; α is the thermal diffusivity of coal, m²/s, calculated as $\alpha = k/(\rho c_p)$, where k is the thermal conductivity, W/(m·K), ρ is the density of tar-rich coal, kg/m³; and c_p is the specific heat capacity, J/(kg·K). In this study, the heater radius is $a = 0.025$ m, and the radial positions of the thermocouples from the center are $r = 0.125$, 0.25, and 0.32 m; therefore, the corresponding distances from the heater surface are $x = 0.10$ m, 0.225 m, and 0.295 m. The thermophysical parameters are $k = 0.21$ W/(m·K), $\rho = 1370$ kg/m³, and $c_p = 1300$ J/(kg·K).

When $x = 0$, the heat-flux density at the heater surface is obtained as:

$$q_w(t) = q(0, t) = k \frac{(T_w - T_0)}{\sqrt{\pi \alpha t}} \quad (2)$$

The heater radius is $a = 0.025$ m, and the surface area per unit length is $2\pi a$; thus, the linear power density can be expressed as:

$$q'(t) = 2\pi a q_w(t) \quad (3)$$

Fig. 8(a) shows the measured heater surface temperature, which remains essentially at 500 °C, except for brief fluctuations at 160 h and 342 h due to equipment maintenance. The time evolution of the line heat-source strength $q'(t)$ calculated using Eqs. (2) and (3) is shown in Fig. 8(b). During 0–0.65 h, because the temperature difference between the coal seam and the heater is the largest and the thermal driving force is strong, the calculated $q'(t)$ increases rapidly and reaches a peak of 0.71 kW/m. As the temperature increases, the temperature difference decreases, and $q'(t)$ drops to 0.024 kW/m at 160 h. Between 160 and 482 h, the linear power density required to maintain the constant temperature is only 0.02–0.03 kW/m. Over the entire conductive-heating process, the average linear power density is approximately 0.052 kW/m. The heater power efficiency is 1.73%, indicating low heat-transfer efficiency; the primary bottleneck limiting heating efficiency is the intrinsic thermal conductivity of the coal seam rather than the heater power capacity.

3.2. Oil and gas generation mechanisms

3.2.1. Recovery ratio of pyrolysis oil and gas

Fig. 9 shows oil and gas production during conductive heating. Fig. 9(a) shows the variation curve of oil and gas production; the cumulative water production is 3.58 L, the cumulative oil production is 0.79 L, and the cumulative gas production is 8.6 m³. From 0 to 249 h, a small amount of volatile and moisture was released. At 160 h, the average temperature of the reactor was 215 °C, and moisture began to be released. At 249 h, the temperature in most areas exceeded 308 °C, and oil started to be released. From 249 to 342 h, the temperature in most areas exceeded 404 °C, and significant amounts of oil and gas were produced. And heavy components began to form from 342 to 424 h. Due to their viscosity and low volatility, their release was hindered. From 424 to 482 h, the maximum temperature is 420 °C. A small amount of oil and gas was rereleased. This was attributed to the secondary cracking of heavy components, which generated additional oil and gas. Overall, the cumulative oil recovery is 1.97%, and the cumulative gas recovery is 27.86%. The low recovery can be attributed to two main factors: (1) incomplete pyrolysis caused by temperature nonuniformity, and (2) pore blockage in the low-temperature regions of the reactor. Both the oil and gas recovery ratios are relatively low.

3.2.2. Components of pyrolysis oil and gas

Fig. 10 shows the components of pyrolysis oil during conductive heating. The composition of the pyrolysis oil was analyzed using GC-MS. Fig. 10(a) shows the total ion chromatogram of the pyrolysis oil, with the main components being alkanes, alkenes, aromatics, phenols, and other compounds, including acids, aldehydes, esters, and alcohols. For ease of analysis, the process from the start of oil production at 249 h to the end of the experiment at 482 h was divided into five stages: early stage, early-mid stage, mid-stage, mid-late stage, and late stage. Additionally, based on the distribution of carbon atom numbers in the pyrolysis oil, it was classified into light oil ($C < 20$) and heavy oil ($C \geq 20$) (Pei et al., 2018).

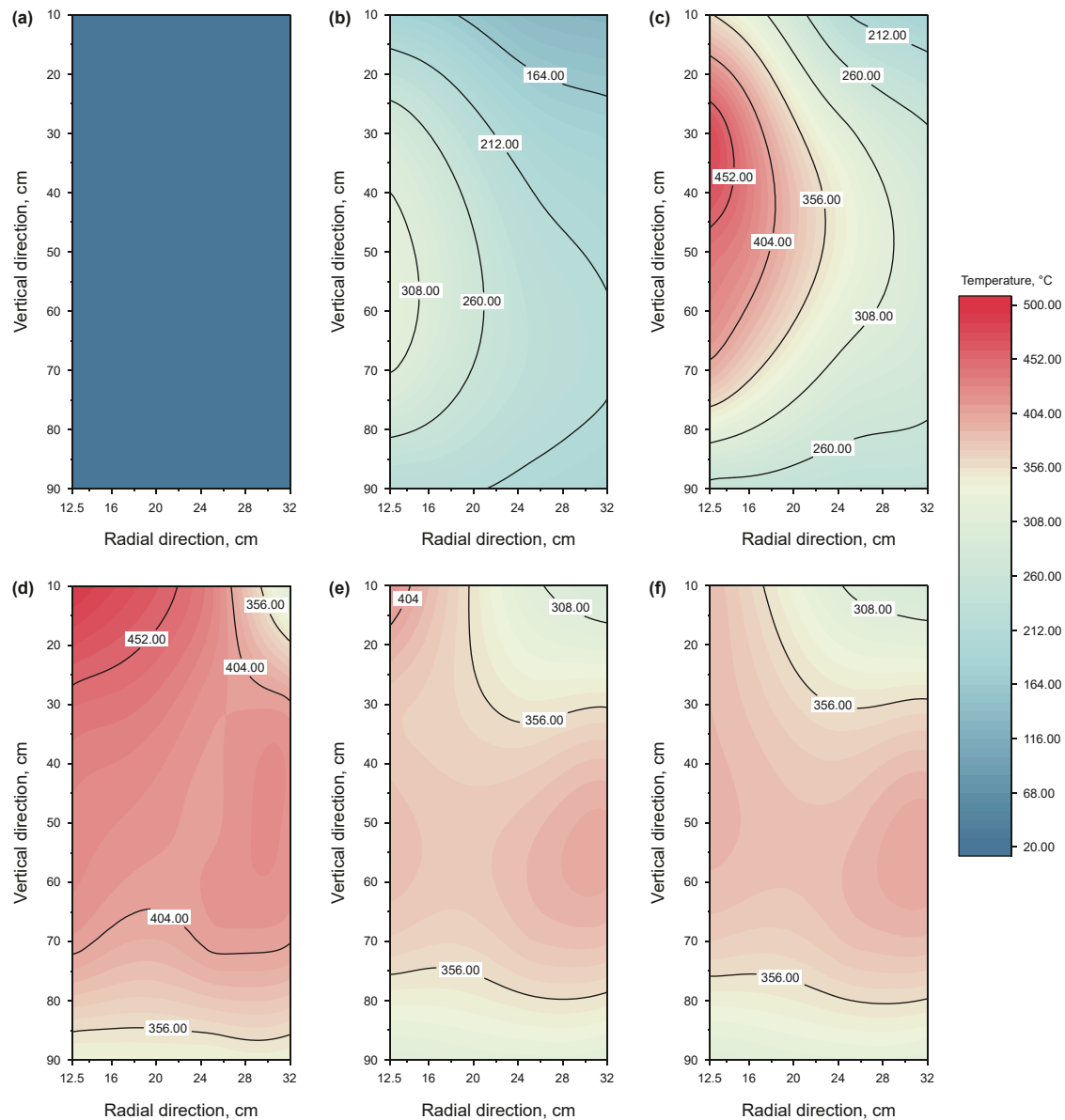


Fig. 7. The temperature field variation map: (a) 0 h, (b) 160 h, (c) 249 h, (d) 342 h, (e) 424 h, (f) 482 h.

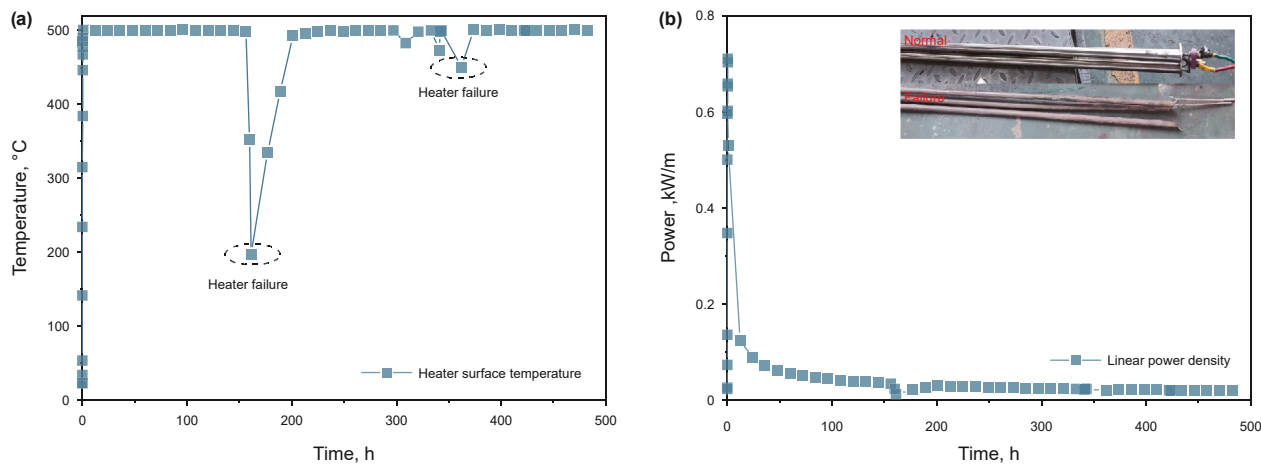


Fig. 8. Variations in heater surface temperature and linear power density. (a) Measured surface temperature, (b) linear power density.

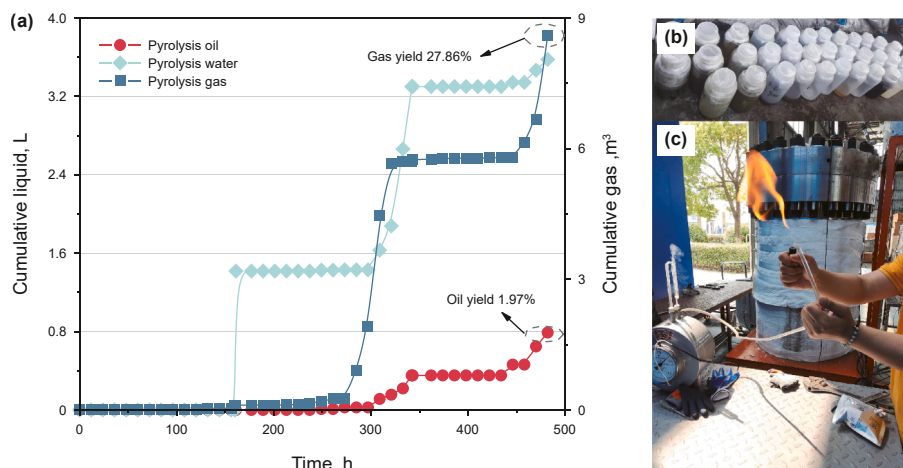


Fig. 9. Oil and gas production during conductive heating. (a) The variation curve of oil and gas production, (b) photograph, (c) photograph of pyrolysis gas combustion.

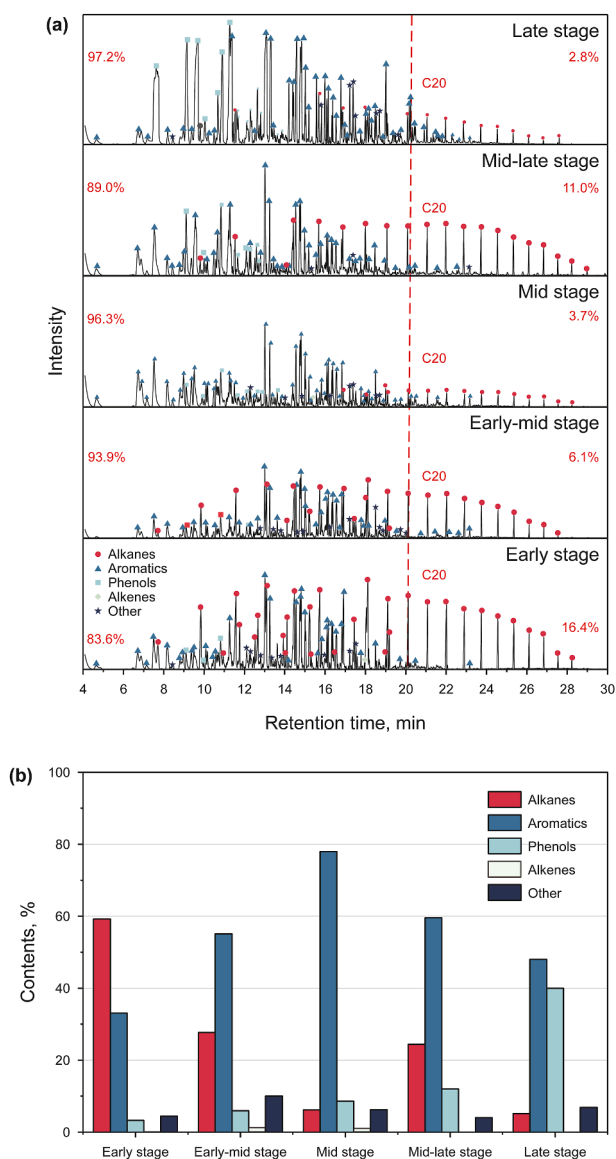


Fig. 10. The component of pyrolysis oil during conductive heating. (a) The total ion chromatogram, (b) the distribution of each component.

As shown in Fig. 10(a), the proportion of light oil ($C < 20$) increased from 83.6% in the early stage to 97.2% in the late stage. The light oil ($C < 20$) reached at 96.3% during the mid-stage. This increase from the early to mid-stage is attributed to the generation of light oil components from the cleavage of aliphatic and aromatic side chains. In the mid-late stage, the proportion of light oil ($C < 20$) decreased to 89.0%, likely due to aromatic condensation and partial cracking of aliphatic chains, generating heavy oil components (Che et al., 2023). In the late stage, the light oil ($C < 20$) increased again to 97.2%, possibly due to the secondary cracking of heavy oil, which led to an increase in light oil.

Fig. 10(b) shows the distribution of each component in the pyrolysis oil. The alkane content decreases from 59.24% in the early stage to 5.17% in the late stage. This is because short-chain alkanes, which are volatile, are primarily generated in the early stage. The alkane content increases to 24.43% in the mid-late stage. Compared with Fig. 10(a), the mid-late stage is characterized by the generation of long-chain alkanes, whereas in the late stage, the alkane content decreases to 5.17% as long-chain alkanes are cracked into short-chain alkanes. The content of aromatic hydrocarbons increased from 33.08% in the early stage to 48.01% in the late stage, reaching a maximum of 77.97% in the mid-stage. From the early to the mid-stage, alkanes undergo aromatization to form relatively stable aromatics. The aromatic content decreases from 77.97% to 48.01% from the mid-stage to the late stage. Compared with Fig. 10(a), the aromatic condensation reactions generate more considerable aromatics, such as $C_{16}H_{14}$, along with others. The phenol content increases from 3.26% in the early stage to 39.95% in the late stage. The increase in phenols may be due to the cleavage of C–O bonds in compounds such as ethers (Lu et al., 2024), accompanied by the generation of more oxygen-containing functional groups, which are fixed by hydrogen radicals.

From the mid-stage to the late stage, phenol increases are attributed to the cleavage and reorganization of aromatics (Webber et al., 2024). The content of alkenes is relatively low, as most alkenes have already transformed into saturated hydrocarbons during the migration of the pyrolysis oil. The content of others is relatively low, resulting from the decomposition of oxygen-containing functional groups and the release of CO_2 . During conductive heating, the pyrolysis oil is primarily composed of light oil, with the main components being alkanes, aromatics, and phenols.

The pyrolysis gas components were analyzed using GC, and the gas components included CO_2 , CH_4 , H_2 , and H_2S , as well as small

amounts of C_2H_4 and C_2H_6 . For ease of analysis and convenience, gases containing C_2 and higher are collectively referred to as C_2-C_6 . Fig. 11 shows the variation curve of pyrolysis gas components during conductive heating. From 0 to 47 h, the gas component is primarily CO_2 , which originates from physically adsorbed gases and from the low-temperature pyrolysis of oxygen-containing functional groups such as carboxyl ($-COOH$) and carbonyl ($-C=O$) groups. (As time progresses, CH_4 begins to form at 52 h, and the CO_2 content gradually decreases. The generation of CH_4 results from the cleavage of aliphatic chains. At 224 h, the CH_4 content peaks at 76.42% and then decreases. The decline in CH_4 content is attributed to the condensation reaction between CH_4 and polycyclic aromatic structures at high temperatures, which consumes methane and forms coke (Fau et al., 2014). The content of H_2 is relatively low between 0 and 261 h, resulting from the H_2 produced by the cleavage of aliphatic C-H bonds and the dehydrogenation of hydrogenated aromatic structures. After 261 h, the H_2 content increases due to H_2 produced by the aromatics condensation reaction (Kang et al., 2025). The content of C_2-C_6 remains relatively low, and the increase in C_2-C_6 components is attributed to the cleavage of long-chain hydrocarbons. The content of H_2S is quite low and begins to appear around 312 h due to the decomposition of organic sulfur compounds, such as thiophene and inorganic sulfur, at temperatures above 400 °C. During conductive heating, the gases mainly consist of CH_4 , CO_2 , H_2 , and C_2-C_6 . Over time, the CO_2 content continuously decreases, the CH_4 content initially increases and then decreases, the H_2 content increases during the mid-stage, and the C_2-C_6 content initially increases and then decreases.

3.3. Characteristics of the reaction zones

3.3.1. Characteristics of pore structure evolution

Fig. 12 shows the CT image of the original sample. The tar-rich coal sample matrix contains pores and inorganic minerals, with organic matter distributed primarily within the matrix. This composition provides a fundamental basis for oil and gas generation (Kang et al., 2024). Some fluid is also present in specific pores. The overall porosity of the sample is 3.63%. Given the Micro-CT scanning resolution of 0.53 μm , in this study, the pore

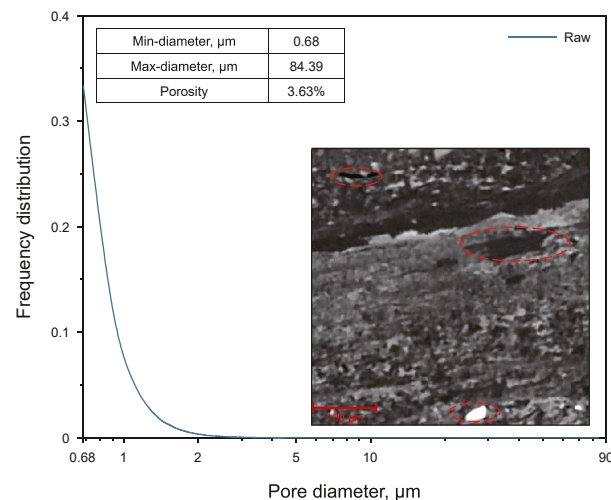


Fig. 12. CT images and pore diameter distribution of the original sample.

structures were categorized by equivalent diameter into three distinct size ranges: $<1 \mu m$, $1-10 \mu m$, and $>10 \mu m$. Pore diameters of the sample range from 0.68 μm to 84.39 μm . Specifically, pores $<1 \mu m$ account for 54.9%, $1-10 \mu m$ for 44.7%, and $>10 \mu m$ for only 0.4%. Therefore, the original pore structure is dominated by pores smaller than 10 μm , whereas those larger than 10 μm are relatively rare, contributing to the overall low porosity (Geng et al., 2017).

Fig. 13 shows the CT images of different zones during conductive heating. In these images, pores are color-coded by size: red denotes pores $>10 \mu m$, purple indicates those between 1 and 10 μm , and green represents pores $<1 \mu m$. Further analysis was conducted on the number of pores and their diameter distribution in different zones during conductive heating. As shown in Fig. 14, as the radial distance increases, the number of pores increases while the pore diameter distribution narrows. Meanwhile, the proportion of pores $>10 \mu m$ gradually decreases, while that of pores $<1 \mu m$ increases. As the vertical distance increases, the number of pores and their size distribution first rise and then fall. Higher values predominantly appear at 30 cm and 50 cm, where the fraction of pores $>10 \mu m$ is relatively high. This zone experiences higher pyrolysis temperatures, inducing pores $<1 \mu m$ to locally interconnect and evolve into the $1-10 \mu m$ range. Furthermore, as pyrolysis products are released, pores in the $1-10 \mu m$ range may coalesce into pores $>10 \mu m$. The largest pore diameter is in the 12.5–30 zone, measuring 168.35 μm . This zone is located near the heat source. In contrast, in the 25–70 and 25–90 zones, the maximum pore diameters are only 26.56 μm and 36.91 μm , respectively. Insufficient pyrolysis in these zones leads to fewer pores. Under high-pressure conditions, pore condensation occurs as volatiles are released, reducing the number of pores. This process causes heavy components to migrate to these areas, hindering their precipitation. During conductive heating, the number of pores and their diameter distribution are closely related to the degree of organic matter pyrolysis. Pore diameters span a broader range in zones where pyrolysis is complete, and the proportion of large pores is higher (Wang et al., 2021).

The formula for calculating permeability during conductive heating process is given in Eq. (4):

$$K = \frac{Q_0 P_0 \mu \ln\left(\frac{d_e}{d_w}\right)}{\pi h (P_1^2 - P_2^2)} \quad (4)$$

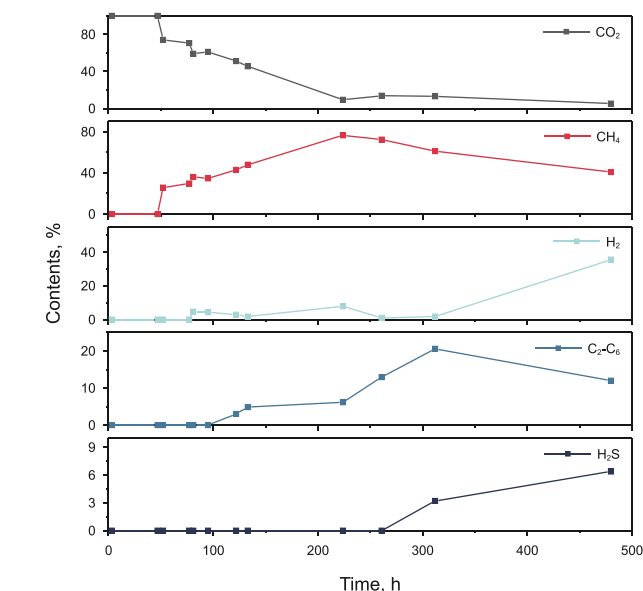


Fig. 11. The variation curve of the pyrolysis gas component during the conductive heating.

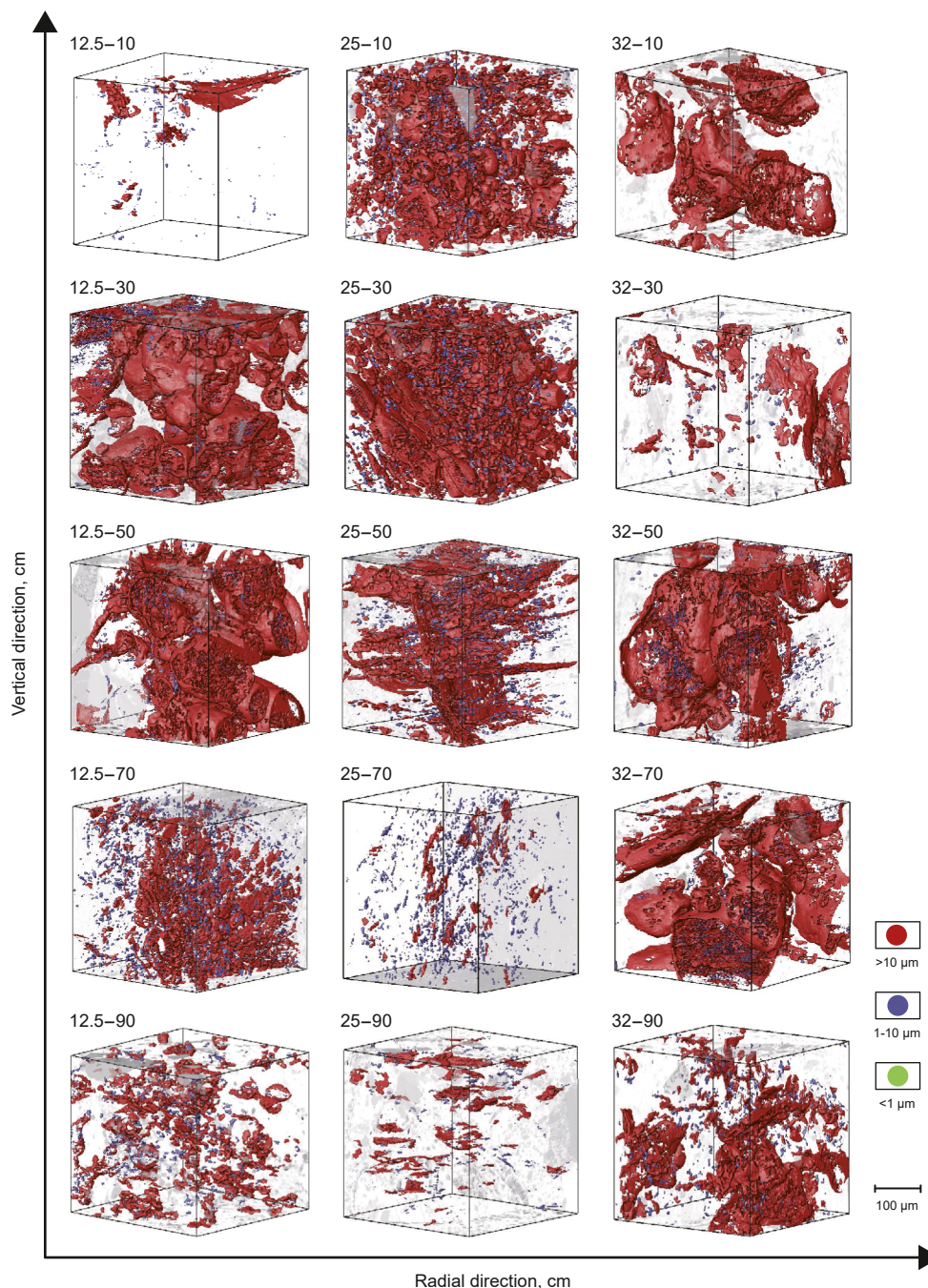


Fig. 13. CT images of different zones during conductive heating.

where Q_0 is the gas flow rate, m^3/s ; P_0 is the experimental pressure, Pa; μ is the gas viscosity, Pa·s; d_e is the outer diameter, m; d_w is the inner diameter, m; h is the thickness of the medium, m; P_1 is the inlet pressure, Pa; P_2 is the outlet pressure, Pa; K is the permeability, m^2 .

Fig. 15 shows the porosity distribution map after conductive heating. The highest-porosity zones, with a maximum porosity of 9.36%, occur around the wellbore due to sufficient pyrolysis in those zones. Lower-porosity zones mainly appear at 32–70 and deeper zones, where the porosity can be as low as 0.25%. In other zones, the porosity remains between 2% and 5%. This low porosity arises from incomplete pyrolysis, which produces fewer pores that are subsequently compressed. Meanwhile, substantial pyrolysis

products migrate and precipitate in these zones, further reducing porosity. During conductive heating, uneven heat distribution significantly affects the spatial distribution of porosity. In zones with sufficient pyrolysis, the porosity is notably higher, whereas in lower-temperature zones, migrating products block pores, resulting in lower porosity.

Fig. 16 shows the variation curve of permeability during conductive heating. Initially, permeability increases, then decreases over time. At 132 h, the permeability is 9.98 mD, accompanied by volatile release, followed by moisture production, and gradually increasing permeability. At 237 h, the permeability reaches 41.02 mD before decreasing. At 321 h, a blockage occurs in the reactor, resulting in a sharp drop in permeability to 0.23 mD.

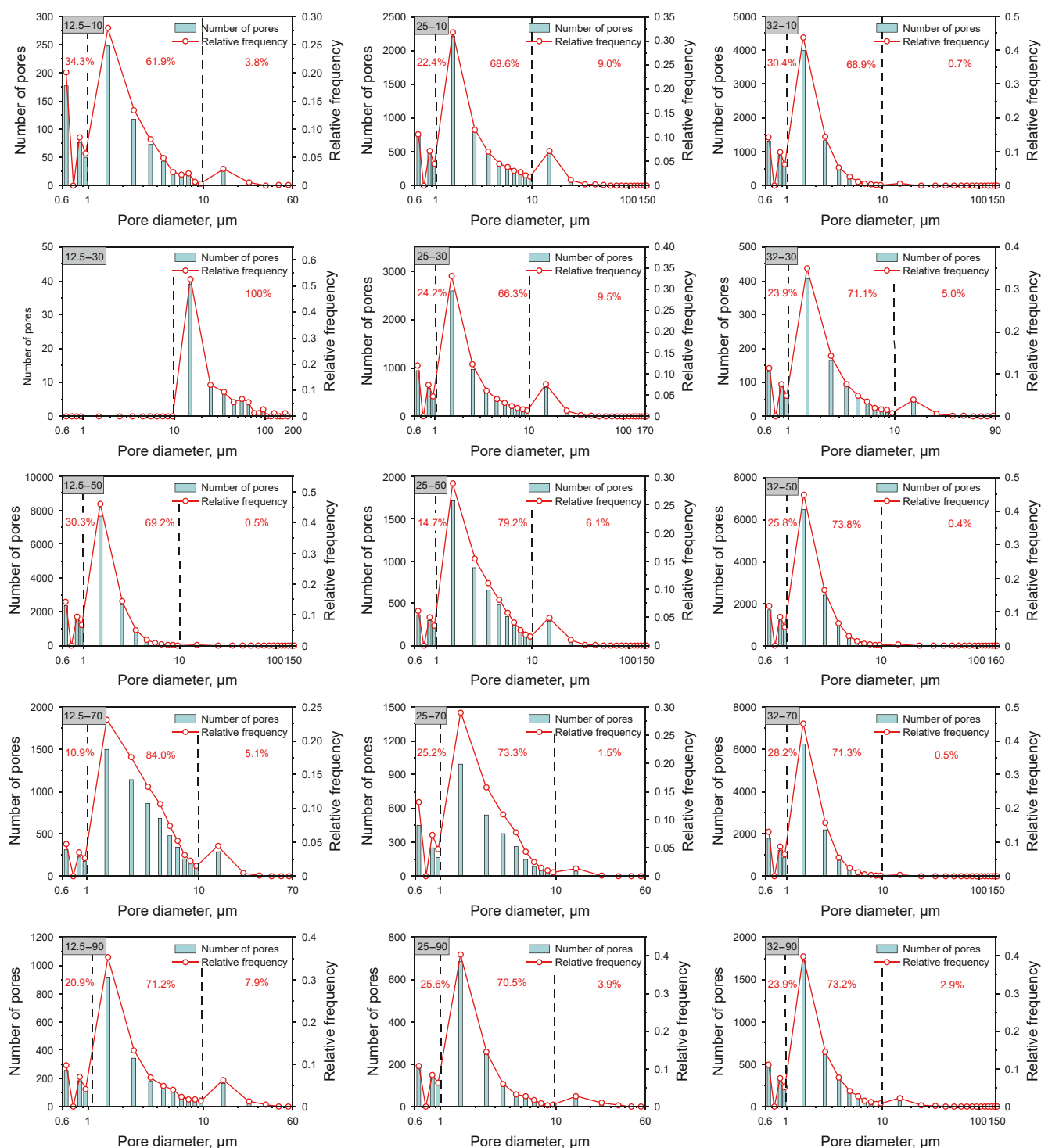


Fig. 14. The variation curve of the number of pores and pore diameter distribution at different zones during conductive heating.

Subsequently, the permeability fluctuates within a low range, never exceeding 3 mD. The average permeability over the entire reaction process was 5.39 mD. The increase in permeability is caused by the release of volatiles and pyrolysis products, whereas the blockage in the reactor stabilizes permeability at a low level.

3.3.2. Evolution characteristics of organic matter

Fig. 17 shows the characteristics of the sample after pyrolysis. Fig. 17(a) shows sampling results from different zones. The

sample is generally dense, with noticeable porosity differences on both sides of the 25–70 and 25–90 zones, suggesting different degrees of pyrolysis.

Fig. 17(b) shows the distribution map of organic matter. The zones with higher free hydrocarbon S1 content are located at the top and bottom of the reactor. The maximum values are 20.35 mg/g at the top and 8.08 mg/g at the bottom. The higher free hydrocarbon S1 content in the top zone can be attributed to the preferential upward migration and accumulation of gaseous and light

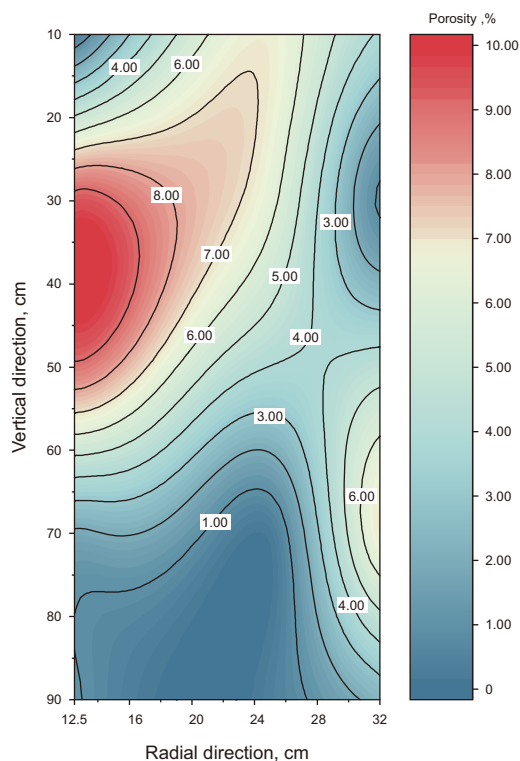


Fig. 15. Porosity distribution cloud map after conductive heating.

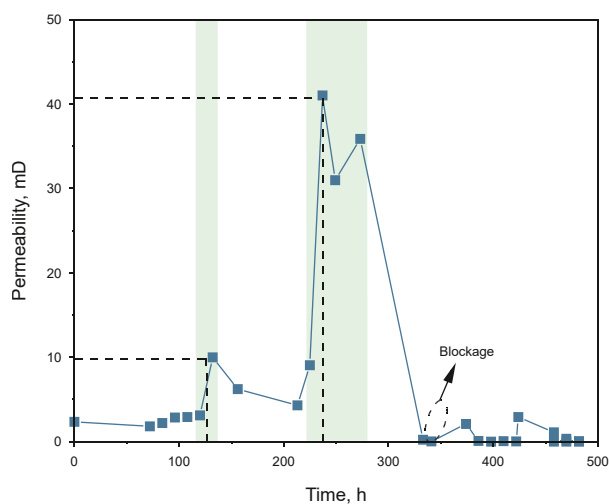


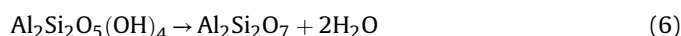
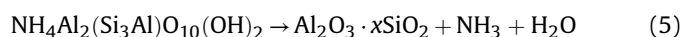
Fig. 16. The variation curve of permeability during conductive heating.

pyrolysis products during pyrolysis. The higher free hydrocarbon S1 content in the bottom zone is due to lower temperatures, causing the produced free hydrocarbons to migrate downward and condense, which is the primary cause of reactor blockage. Higher pyrolysis hydrocarbon S2 content is concentrated in the 25–30 and 25–70 zones, with a maximum of 119.68 mg/g at the top and 99.59 mg/g at the bottom. This is because the temperature in these zones is typically below 370 °C, preventing the complete conversion of organic matter. The higher content at the top may be due to organic matter that has not been wholly converted under low-temperature conditions. In comparison, the higher content at the bottom may be related to the migration of complex macromolecular compounds to this zone, which is difficult to degrade (Xu

et al., 2023). The temperature and migration of products play a crucial role in transforming organic matter and its spatial distribution. Pyrolysis characteristics differ significantly between the top and bottom zones. These findings guide optimizing well placement and selecting pyrolysis processes.

3.3.3. Evolution characteristics of inorganic minerals

Fig. 18 shows the distribution map of inorganic minerals. The variation trends of kaolinite and tobelite exhibit opposite patterns. Zones with higher concentrations of tobelite are located at the top, with a maximum concentration of 18.21%. Tobelite has low thermal stability at elevated temperatures. Within the 300–600 °C range, Tobelite transforms into amorphous aluminosilicate via deammoniation and dehydroxylation reactions (Liu et al., 2015), as shown in Eq. (5). Kaolinite has relatively stable properties, and its content remains between 75% and 90%. The decomposition (dehydroxylation) of kaolinite typically occurs between 450 °C and 600 °C, leading to the formation of amorphous aluminosilicates (metakaolin), as shown in Eq. (6). Calcite is relatively stable, with a decomposition temperature above 600 °C. During conductive heating, calcite does not decompose. The variation trends of pyrite and pyrrhotite exhibit opposite patterns. As shown in Eq. (7), pyrite can directly transform into pyrrhotite. Higher concentrations of pyrite are mainly found in zones 25–10 and 25–90, with corresponding concentrations of 0.77% and 0.25%. Pyrite has not entirely decomposed. The decomposition temperature of pyrite in its pure form ranges from 400 °C to 600 °C. When coexisting with organic matter, it acts as a reducing agent, lowering the decomposition temperature of pyrite (Schill et al., 2002). Comparing pyrrhotite content, pyrrhotite produced at higher temperatures in zones 12.5–30 and 25–30 shows higher concentrations. This confirms that the formation of pyrrhotite from pyrite is controlled solely by the highest temperature, while the duration of high temperatures determines the amount of pyrrhotite produced (Wang et al., 2014). During conductive heating, inorganic minerals undergo mutual transformation, whereas the rock framework of tar-rich coal, such as kaolinite, shows little decomposition. This result confirms that the accumulation of heavy components causes the blockage phenomenon.



3.4. Discussion

3.4.1. Heat transfer mechanism of tar-rich coal during in situ pyrolysis

The heating rate is low, resulting in slow heat transfer and low efficiency. The pressure changes remain relatively stable. This can be attributed to the thermophysical properties of tar-rich coal, consistent with findings reported in the literature (Ali and Bayestehparvin, 2018). This experiment was conducted under high pressure. According to the literature (Hofmeister, 1999), when pressure increases by 1 GPa, thermal conductivity only increases by 4%, indicating that pressure has only a minor effect on thermal conductivity and conductive heat transfer under the experimental pressure range.

The initial heating rate is slow, primarily due to the high specific heat capacity of tar-rich coal. The experimental samples contain high moisture and volatile matter, which enhance their

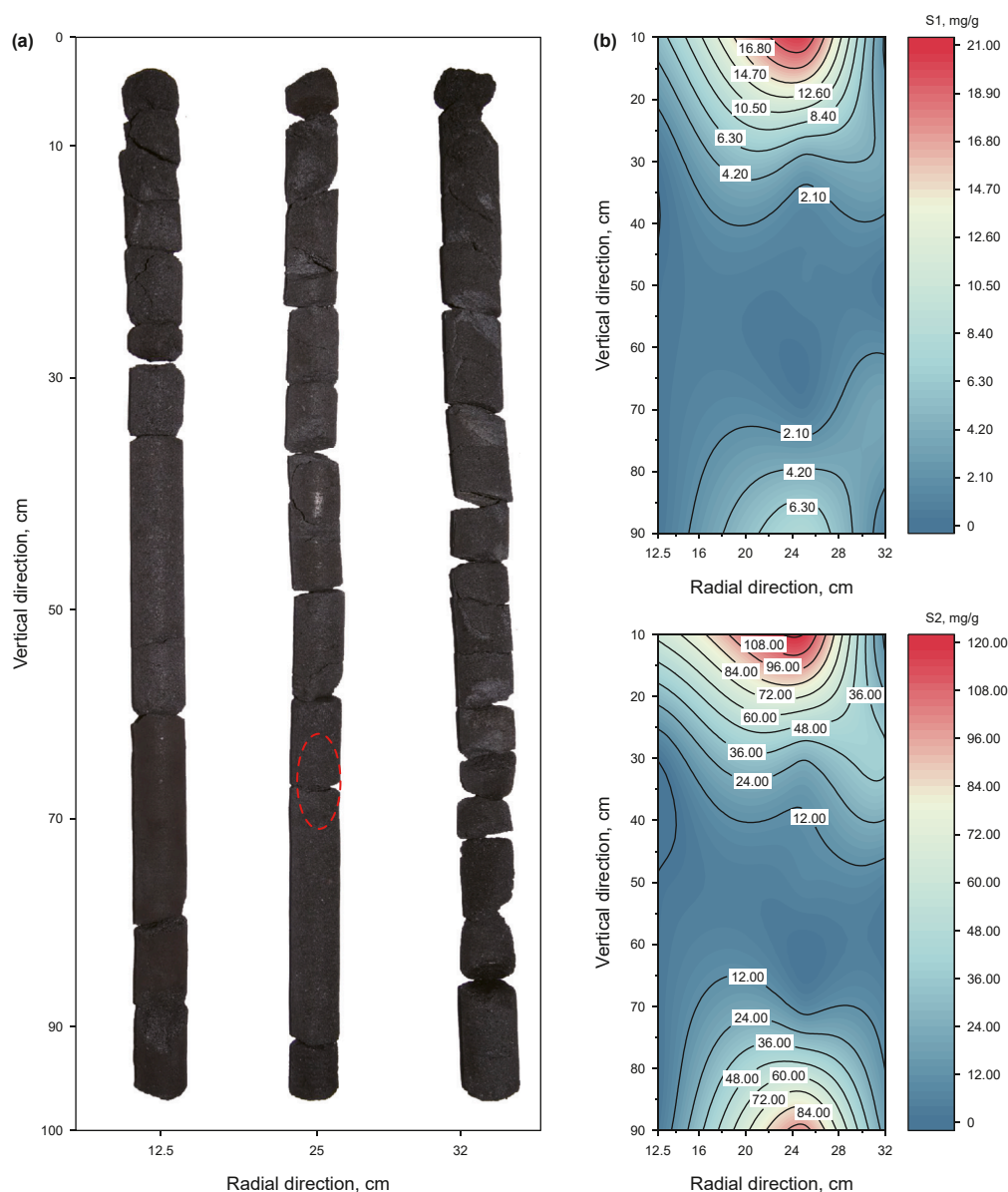


Fig. 17. The sample characteristics after pyrolysis. (a) Sampling results from different zones, (b) distribution map of organic matter.

heat absorption capacity, consistent with findings reported in the literature (Deng et al., 2017). As the temperature increases, the specific heat capacity also increases, leading to a significant decrease in the heating rate during the later stages.

The slow temperature transfer is influenced by thermal conductivity. According to the literature (Zhang et al., 2023), the maceral components of coal affect its thermal conductivity. As the temperature increases, the minerals and inertinite heat up quickly, while the vitrinite group heats up more slowly. The sample in this experiment contains a high proportion of vitrinite, leading to localized heating in the early stages and a larger average temperature difference in the reactor. As the pyrolysis temperature increases, vitrinite continues to undergo pyrolysis, improving the thermal conductivity of the maceral components. This is consistent with findings reported in the literature (Urquhart and Bauer, 2015). The temperature difference influences temperature transfer, and the temperature tends to stabilize in the later stages. However, due to incomplete pyrolysis and the higher percentage of vitrinite, the temperature required for equilibrium is lower.

The thermophysical properties of tar-rich coal and heat source density influence low-temperature transfer efficiency. Thermal diffusivity decreases as pyrolysis temperature increases. Initially, heat injection is sufficient, and heater efficiency is high. However, when thermal equilibrium is reached, heater efficiency decreases significantly, consistent with findings in the literature (Wei and Liu, 2023). Literature (Su et al., 2020) indicates that increasing heat source density enhances heat transfer efficiency, but the degree of improvement is limited. Heat conduction mainly generates Joule heat through conductors, heating the coal seam through resistance loss, and coal absorption. This study found that a large amount of heat cannot be absorbed by the coal seam in time, resulting in low heater efficiency and decreased power consumption. Ultimately, this leads to insufficient heat injection capacity.

3.4.2. Blockage mechanism of tar-rich coal during in-situ pyrolysis

During conductive heating, as pyrolysis products migrate to the production well, heavy components condense and accumulate

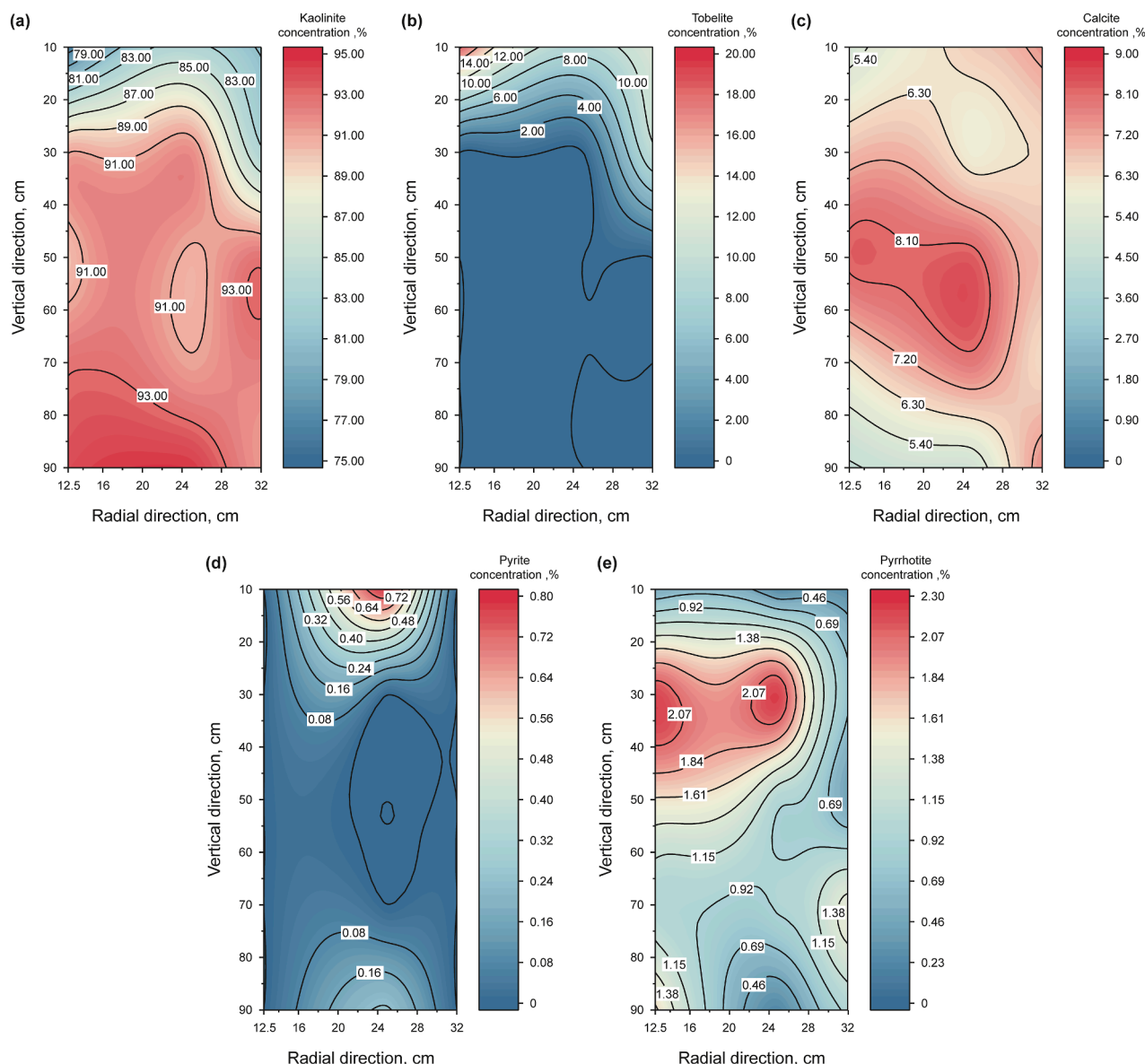


Fig. 18. The distribution cloud map of inorganic minerals.

around the well. Based on experimental results, in-situ pyrolysis of tar-rich coal can be divided into three stages: (a) thermal expansion and light component release, (b) rapid pyrolysis, and (c) stable pyrolysis. As shown in Fig. 19, the thermal expansion and light component release stage occurs in the 25–200 °C temperature range. The thermal expansion effect induces thermal fracturing of tar-rich coal, accompanied by the release of volatile gases, consistent with the findings of reference (Kang et al., 2022). When the pyrolysis temperature exceeds 300 °C, the release of volatiles and the pyrolysis of organic matter intensify, causing compression deformation in local zones and a reduction in pore space. The pyrolysis products migrate and eventually reach the production well, where they are extracted. In the rapid pyrolysis stage, the pyrolysis temperature exceeds 450 °C around the injection well, and a significant nonuniformity in pyrolysis is observed. Organic matter rapidly decomposes to generate hydrocarbon gases and oil, while inorganic minerals, such as FeS_2 , decompose to produce H_2S . Organic matter continues to undergo pyrolysis, further compressing the pore structure in zones below 400 °C, although the

degree of pyrolysis remains relatively low. The generated heavy components undergo secondary cracking during migration, accompanied by condensation to form sizeable molecular coke. Small molecules migrate smoothly, while large molecules are retained around the production well due to condensation, causing partial pore blockage. This limits the further release of pyrolysis products (Guo et al., 2023b). In the stable pyrolysis stage, organic matter continues to undergo pyrolysis, further compressing the pore structure. The pyrolysis products undergo secondary cracking and coke polycondensation during migration. The migration efficiency of light components is relatively high, while heavy components condense and accumulate in the low-temperature zone, eventually leading to complete blockage. It can be noted that blockage generally occurs during the rapid pyrolysis and stable pyrolysis phases. This study found that the blockage is concentrated in the low-temperature zone around the production well, which differs from Zhu's (Zhu et al., 2025) finding that the blockage occurs in the flow channels. The blockage is mainly caused by the thermal expansion effect of clay minerals, as

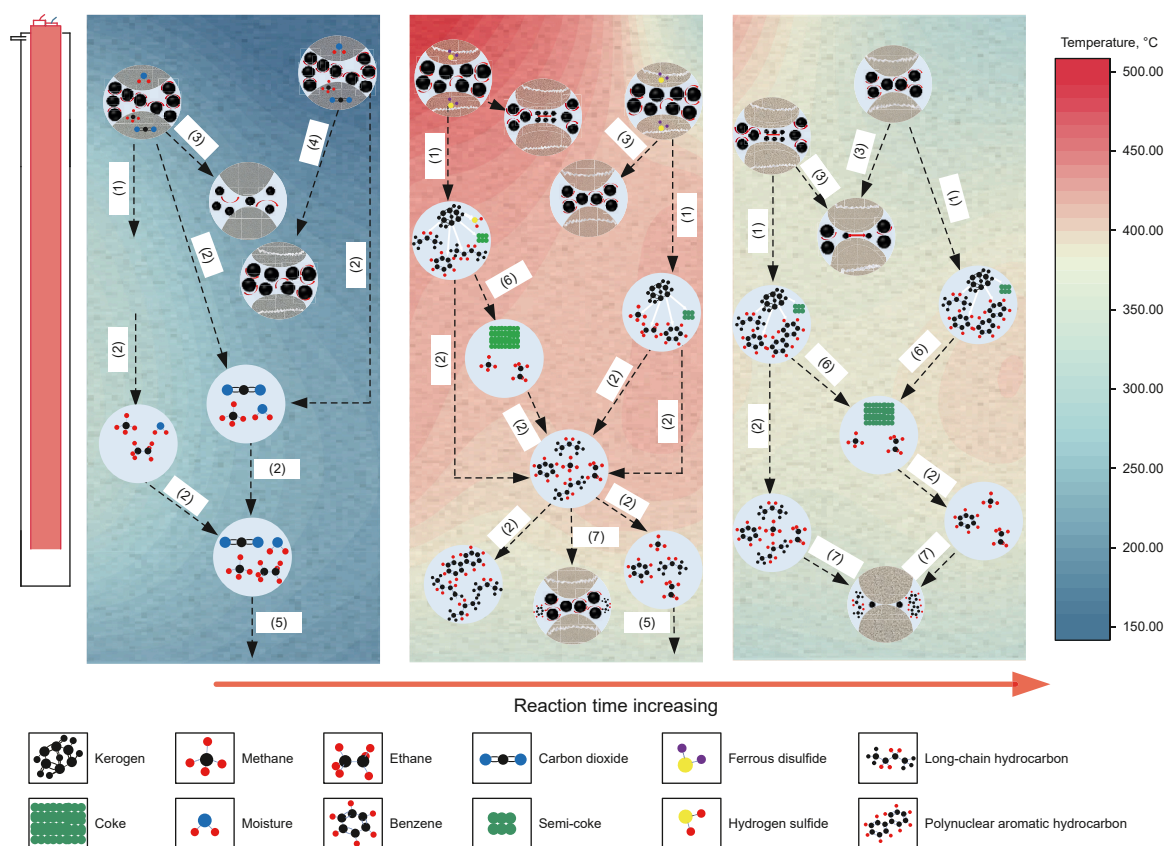


Fig. 19. Blockage mechanism of tar-rich coal in-situ pyrolysis. (1) Organic matter pyrolysis, (2) oil and gas migration, (3) pore reduction, (4) thermal fracture, (5) product release, (6) secondary cracking, (7) pore blockage.

suggested by previous studies (Guo et al., 2017), possibly since clay minerals did not undergo significant decomposition in this study.

During conductive heating, the migration of pyrolysis products depends on their gravity and the pressure generated by gas expansion. The migration efficiency of large and small molecules differs significantly. In the low-temperature zone around the production well, where temperatures are below 350 °C, large molecules accumulate through condensation, limiting the further migration of the products. Thus, the low temperature in the unpyrolyzed zone is the primary cause of blockage.

3.4.3. Guidance for engineering practice

Based on the aforementioned results and discussions, the following process optimization measures are suggested to enhance oil and gas production in the in-situ pyrolysis of tar-rich coal during conductive heating:

First, reservoir modification optimization should be performed, and precise reservoir modification techniques should be applied to enhance the seepage characteristics of the formation. Additionally, high-conductivity proppants should be injected into fractures to improve thermal conductivity, ensure efficient heat transfer, and facilitate the smooth extraction of pyrolysis products along the channels. Second, if a horizontal well is selected, it should be evenly arranged above the heating well to ensure the efficient production of pyrolysis products migrating upward. Lastly, reservoir sealing technology should effectively insulate the area around the production well, minimizing heat loss and improving overall pyrolysis efficiency.

It is important to note that these recommendations are based on the results of this study and should take into account the

geological conditions of the tar-rich coal seams in practical applications. In addition, the feasibility of co-production should be evaluated, considering the groundwater system, stress conditions, formation stability, and potential environmental pollution risks.

4. Conclusions

This study used a self-designed high-temperature, high-pressure, in-situ pyrolysis experimental apparatus for tar-rich coal to conduct conductive heating experiments. It analyzed the temperature and pressure characteristics, oil and gas production mechanisms, and reaction zone characteristics during the in-situ conversion process. The main conclusions are as follows:

- (1) The heating rate is slow, averaging 0.70 °C/h, which leads to slow heat transfer, with the maximum temperature difference exceeding 280 °C, resulting in temperature transfer efficiency being low, with a heater power efficiency of just 1.73%. This results in insufficient heat injection capacity. Increasing the wellbore temperature or using convection to improve heat transfer is recommended. Pressure fluctuations are minimal, with an average pressure difference of 0.18 MPa.
- (2) The oil recovery is only 1.97%, and the gas recovery is 27.86%, indicating a low recovery. The oil consists of light components, with the pyrolysis oil mainly composed of alkanes, aromatics, and phenols. Early-stage gas production is dominated by CO₂ and CH₄, whereas later-stage gas production is primarily CH₄ and H₂.

- (3) Gaseous and light pyrolysis products preferentially migrate upward and ultimately accumulate near the top. The production wells will be arranged above the heating wells in future operations. Inorganic minerals undergo mutual transformation, but the rock framework of tar-rich coal, such as kaolinite, shows no significant decomposition.
- (4) The temperature around the production well remains low, resulting in fewer pores and a narrower pore diameter range, which leads to lower porosity, locally as low as 0.25%. When pyrolysis products migrate to the production well, heavy components condense and accumulate around it, causing pore blockage. Although releasing volatiles and pyrolysis products can enhance permeability, blockages in the reactor ultimately keep it at a low level.

CRediT authorship contribution statement

Yan-Wei Li: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Chao-Fan Zhu:** Writing – review & editing, Writing – original draft, Supervision, Software, Data curation. **Cun-Han Fan:** Software, Methodology, Investigation, Data curation. **Tian-Le Zhang:** Software, Formal analysis, Data curation. **Han Tian:** Methodology, Formal analysis, Data curation. **Yi-Jian Zeng:** Formal analysis, Data curation. **Wei Guo:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge the financial support offered by the project of CNOOC Gas & Power Group Co. (GP-YF-CBZB-2023-030/01), the Key R&D projects of Jilin Provincial Science and Technology Department (Grant No. 20230203121SF), and the National Oil Shale Exploitation R&D Center Open Fund Project (Grant No. 33550000-24-ZC0613-0055).

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