Research of New Cross-Flow Technology with a Gas Heat Carrier for Lignite Pyrolysis

Tao Fan, Mo Chu,* and Zhibing Chang

ABSTRACT: The adaptability of the gas heat carrier cross-flow pyrolysis process to Huolinhe lignite (0−80 mm) and the influence of the temperature of the heat carrier and moisture of the raw materials on the yield and properties of the pyrolysis products were studied using a 30 t/d cross-flow pyrolysis pilot plant with a gas heat carrier. When the temperature of the gas heat carrier was increased from 750 to 850 °C, the volatiles (Vdaf) produced from the char decreased from 16.81 to 10.57%, the yield of tar (Tar) increased from 73.81 to 81.1% of the Gray-King (G-K) tar yield, and the yield of gas decreased from 1312 to 1205 Nm³/t. When the temperature of the gas heat carrier was constant at 850 °C and the moisture content (Mt) of lignite was reduced from 12.49 to 7.14%, the Vdaf of char declined from 10.57 to 6.59%, the yield of gas was reduced from 1205 to 805 Nm³/t, the calorific value of gas increased from 3.88 to 4.68 MJ/m³, and the Tar increased to 81.56% of the G-K tar yield. The light tar content (boiling point below 360 °C) was more than 60%, and the ash content was less than 0.04%. The cross-flow pyrolysis moving bed could effectively treat full-size lignite, afforded continuous and stable operation, and provided a high oil and gas yield, which provides basic data for further industrial design.

1. INTRODUCTION

Lignite with high-moisture, high-ash, high-volatiles, and easy self-ignition characteristics, among other features, is not suitable for long-distance transport and long-term storage, limiting its industrial utilization.1−3 As a thermal processing conversion method, the pyrolysis of lignite is one effective way to efficiently utilize lignite, as the processing conditions are mild, the operation is simple, and the products are retrievable.4−6

Coal pyrolysis techniques were developed mainly based on the particle size. These processes include LR, Toscoal, DG, COED, LFC, GF-1, SJ, MRF (see abbreviations), and so on.7−12 At present, LFC, GF-1, SJ, and other processes are established for industrial lignite pyrolysis in China, where these processes are mainly applicable to large particles (30−80 mm).13 Due to the thermal fragility of lignite, the large amount of dust generated in the pyrolysis process leads to oil−gas flow short circuit and blocks the gas pipeline, interrupting stable and continuous system operation.14−16 The solid heat carrier pyrolysis process and the circulating fluidized bed pyrolysis process are mainly used for the pyrolysis of lignite with a small particle size.17−19 Various pilot-scale tests were carried out in China, including the construction of a 1000 t/d moving bed pyrolysis pilot plant by the Process Engineering Research Institute of the Chinese Academy of Sciences,20 a 2 t/d solid heat carrier pyrolysis plant by the Engineering Thermophysics Research Institute of the Chinese Academy of Sciences,21 and a 2 t/d external thermal internal rotating moving bed pyrolysis pilot plant by the Coal Science and Technology Research Institute Co., Ltd., Coal Chemical Industry Branch.22 However, all of these studies are in the laboratory and pilot test stages, and there is no mature pyrolysis technology for realizing industrial operations.23 The research and development of lignite pyrolysis technology faces three main challenges: (1) with the popularization of mechanized coal mining technology, the block rate of lignite is very low.24,25 A large number of small particles cannot be fed into the pyrolysis reactor to participate in the pyrolysis reaction directly but can only be used as power plant coal.26 (2) Lignite is highly thermally fragile;27 the dust produced in the pyrolysis process changes the flow path of oil−gas in the pyrolysis reactor, thereby short-circuiting the gas flow, increasing the resistance of the material layer, and blocking the gas pipeline, which together prevent the
continuous and steady pyrolysis process. Lignite tar contains a lot of dust, which is extremely difficult to separate. These limitations reduce the quality and utilization of tar.

In order to solve the technical problem related to obtaining high-quality tar and gas from full-sized lignite pyrolysis, the China University of Mining and Technology (Beijing) and Beijing Detianyu Investment Management Co., Ltd. jointly developed a cross-flow pyrolysis process with a gas heat carrier for lignite and built a 30 t/d pilot plant, using a moving bed design.

By regulating the direction of flow of the gas heat carrier in the material layer, the thickness and resistance of the layer were substantially reduced while accelerating the rate of thermal reaction of lignite. This technology shortened the residence time of pyrolysis oil and gas in the pyrolysis zone, thereby reducing the secondary pyrolysis of tar and improving the yield of tar. The porous structure of lignite was used to remove dust in the oil–gas, and further dust removal was carried out in the gas collection chamber to resolve the issues of dust related to tar.

In this study, using this pilot plant, the effects of the temperature of the gas heat carrier and the moisture content of the raw materials based on the characteristics of the pyrolysis products and the temperature field in the pyrolysis zone are investigated. The feasibility of this technology is verified, and a basis for further advancing the design is provided.

2. RESULTS AND DISCUSSION

2.1. Temperature Distribution Characteristics. The cross-flow pyrolysis moving bed uses a gas heat carrier to provide energy for heating and pyrolysis of lignite. Because the temperature of the gas heat carrier is reduced during heat transfer in the pyrolysis zone, evaluating the temperature-field distribution in the pyrolysis zone provides a guide for achieving rapid heating of the lignite and estimating the degree of pyrolysis. In this study, raw material A was used for experimental study of cross-flow pyrolysis in the moving bed,
Table 1. Products Yields for Different Pyrolysis Conditions

| Coal | char (wt %, d) | tar (wt %, d) | water (wt %, d) | pyrolysis gas (Nm³/t, d) | recycle gas (Nm³/t, d) | burning gas (Nm³/t, d) |
|------|---------------|--------------|----------------|-------------------------|-----------------------|------------------------|
| A 750 | 65.78         | 4.96         | 8.62           | 1312.02                 | 708.48                | 603.52                 |
| A 850 | 62.43         | 5.45         | 8.89           | 1007.24                 | 515.78                | 491.46                 |
| B 850 | 61.70         | 5.50         | 9.58           | 899.87                  | 426.88                | 473.07                 |
| C 850 | 61.58         | 5.53         | 10.01          | 805.59                  | 372.87                | 432.72                 |

Table 2. Proximate Analysis of Huolinhe Char

| Coal | M₀ (wt %) | A₀ (wt %) | Vdaf (wt %) | FCdaf (wt %) |
|------|-----------|-----------|-------------|--------------|
| A 750 | 2.62      | 30.65     | 16.81       | 83.19        |
| A 850 | 2.05      | 32.11     | 10.57       | 89.43        |
| B 850 | 2.08      | 32.84     | 8.08        | 91.92        |
| C 850 | 2.10      | 33.57     | 6.59        | 93.41        |

Table 3. Particle Size Analysis of Huolinhe Char

| particle size (wt %) |
|----------------------|
| 0–1 mm | 1–3 mm | 3–6 mm | 6–13 mm | 13–25 mm | 25–50 mm |
| A 750 | 10.35 | 7.39   | 15.71   | 34.03    | 22.43     | 10.06    |
| A 850 | 11.92 | 8.43   | 17.30   | 33.12    | 20.28     | 8.95     |
| B 850 | 12.52 | 8.85   | 17.99   | 34.11    | 20.69     | 5.84     |
| C 850 | 13.14 | 9.21   | 18.71   | 34.80    | 20.07     | 4.08     |

by changing the temperature of the gas heat carrier (750 and 850 °C). In the stable operation stage with various process conditions, the temperature at the main measuring point in the moving bed was monitored continuously for 72 h, as shown in Figure 2. The temperature-field distribution characteristics in the pyrolysis zone are shown in Figure 2.

The pyrolysis furnace was fed in the cold state, as illustrated in Figure 1. The maximum deviation from the target temperature was 30 °C, and the temperature was stable during continuous operation, which satisfies the requirements for experimental research. At A750, the average measured temperature of the gas heat carrier was 758 °C, the average final pyrolysis temperature was 553 °C, the average temperature of the lower part of the gas collection chamber was 263.64 °C, and the average temperature of the gas outlet was 174.28 °C. At A850, the average measured temperature of the gas heat carrier was 850.48 °C, the average final pyrolysis temperature was 611.38 °C, the average temperature of the lower part of the gas collection chamber was 353.12 °C, and the average temperature of the gas outlet was 219.55 °C. Lignite had the highest tar yield at 480–520 °C, and the final pyrolysis temperatures of A750 and A850 reached this temperature range.

The pyrolysis furnace was fed in the cold state, as illustrated in Figure 2. As the material moved down, the temperature of the coal increased gradually under the effect of the gas heat carrier. Along the direction of the gas heat carrier temperature flow, the temperature gradually decreased, and the higher the temperature, the narrower the temperature range.

At the bottom of the pyrolysis zone, when the temperature of the gas heat carrier was 750 °C, the temperature of the sidewall of the gas gathering chamber was 350 °C, where lignite pyrolysis had already begun. When the temperature of the gas heat carrier reached 850 °C, the temperature of the sidewall of the gas gathering chamber was 520 °C, indicating that the raw coal in the pyrolysis area had fully reacted at this time.

2.2. Pyrolysis Product Distribution. The results of four typical tests with heat carrier temperatures of 750 and 850 °C and the product distribution are shown in Table 1. When the temperature of the gas heat carrier was increased from 750 to 850 °C, the char yield declined from 65.78 to 62.43%, the tar yield increased from 4.96 to 5.45% (about 81.1% of the G-K tar yield), the yield of pyrolysis water increased from 8.82 to 8.89%, and the gas output was reduced from 1312 to 1205 Nm³/t. This is due to more complete pyrolysis, as the heat carrier temperature increases, which leads to a small increase in the tar and pyrolysis water, reduction of char, increase in the calorific value of pyrolysis gas, reduced gas consumption, and reduced gas production.

The experimental results for A850, B850, and C850 show that as the moisture of the raw materials decreased, the char yield decreased from 62.43 to 61.58%, the tar yield increased from 5.45 to 5.53%, the yield of pyrolysis water increased from 8.89 to 10.01%, and the output of barren gas decreased from 1205 to 805.59 Nm³/t. The moisture in the raw coal will absorb significant amounts of heat during the pyrolysis process. When the moisture content is lower, the heat demand for pyrolysis and the amount of heat carrier are reduced, thereby decreasing the raw gas output. At the same temperature of the gas heat carrier, lower moisture in the raw materials leads to a higher final pyrolysis temperature and lower char yield but higher yields of tar and pyrolysis water.

2.3. Char. 2.3.1. Proximate Analysis. Table 2 shows the results of the proximate analysis of char in each pyrolysis test.

After the pyrolysis of Huolinhe lignite in the cross-flow pyrolysis moving bed with the gas heat carrier at 750 and 850 °C, the volatile content (Vdaf) of the char decreased, reaching a minimum of 6.59% at C850. The ash content (A₀) of the char was higher than 30%, which was determined with the ash content of the raw materials. Increasing the temperature of the gas heat carrier and reducing the moisture content of the raw material were beneficial to the pyrolysis reaction. The parameters for the char products from the cross-flow pyrolysis reaction device covered a wide range, which could be controlled by adjusting the process conditions.

2.3.2. Particle Size Analysis. Table 3 shows the results of particle size analysis of char from the test process. Because the lignite was fragmented during pyrolysis, all char samples comprised particles with sizes of 50–80 mm. The main particle sizes of the char samples were concentrated in the range of 3–25 mm, comprising more than 70%. The higher the temperature of the gas heat carrier, the stronger the fragmentation. The number of particles smaller than 6 mm increased, but particles of all other sizes decreased with increasing temperature; specifically, the fraction larger than 25–50 mm dropped below 10%. The lower the moisture content of the raw materials, the more extensive the fragmentation, the higher the content of small particles, and
the lower the content of large particles in the char.\textsuperscript{37} When the moisture content of the raw coal was 7.14%, the proportion of particles <3 mm in the char was as high as 22.35%, while that >25 mm comprised only 4.08%.

2.4. Pyrolysis Gas. The gas samples generated under the typical process conditions were selected for analysis, and the results are shown in Figure 3. The pyrolysis gas was mainly composed of N\textsubscript{2}, CO\textsubscript{2}, CO, H\textsubscript{2}, CH\textsubscript{4}, and C\textsubscript{n}H\textsubscript{m} and the content of the effective gas components (CO, H\textsubscript{2}, CH\textsubscript{4}, and C\textsubscript{n}H\textsubscript{m}) was low. The pyrolysis gas had a low caloric value of 3.29–4.68 MJ/Nm\textsuperscript{3}, making it applicable as industrial gas. When the moisture content of the raw materials was kept constant, raising the temperature of the gas heat carrier from 750 to 850 °C caused the content of effective gas components in the pyrolysis gas to increase by 11.94%, and the caloric value increased by 17.89%. More specifically, H\textsubscript{2} and CH\textsubscript{4} were mainly derived from the condensation of the polyaromatic structure at high temperatures. The intensification of condensation reaction at 850 °C increased the H\textsubscript{2} and CH\textsubscript{4} yields. The additional CO\textsubscript{2} and C\textsubscript{n}H\textsubscript{m} at 850 °C were mainly the product of volatile decomposition. For lignite pyrolysis in the cross-flow pyrolysis moving bed reactor, the volatile products need to pass through a high-temperature channel before being collected. The decarboxylation of carboxyl compounds and breakage of aliphatic branched chains became more serious and produced more CO\textsubscript{2} and C\textsubscript{n}H\textsubscript{m}.

When the temperature of the gas heat carrier was kept constant, as the moisture of the raw materials decreased, the content of N\textsubscript{2} in the pyrolysis gas decreased (CO, H\textsubscript{2}, CH\textsubscript{4}, C\textsubscript{n}H\textsubscript{m}, and CO\textsubscript{2}) and the caloric value of the gas increased gradually. These results show that increasing the gas heat carrier temperature and decreasing the moisture of the raw materials were beneficial to the pyrolysis reaction, which is consistent with the previous conclusion.

2.5. Tar. 2.5.1. Fundamental Properties. The tar and water were collected in a tar separation tank for separation. The basic properties of the tar samples produced by varying the temperature of the gas heat carrier were analyzed, as summarized in Table 4. The densities of all tar samples were higher than those of water, which facilitated the effective separation of tar and water. The water content of the tar samples was relatively high: 4.09% at 750 °C and 6.99% at 850 °C. The ash content of the tar was low, 0.03% at 750 °C and 0.04% at 850 °C. This shows that the dust removal structure in the cross-flow pyrolysis moving bed is highly effective. Using the porous structure of lignite char, Du Xin et al. designed a granular bed filter for the purification of pyrolysis gas containing dust. The total dust removal efficiency of the whole system was as high as 99.89%.\textsuperscript{38} The content of toluene-insoluble species in the tar was low: 2.34% at 750 °C and 4.43% at 850 °C. The moisture content of lignite tar was higher than the metallurgical industry standard for coal tar (YB/T 5075-2010), and further dehydration treatment was needed. The other indexes were better than the industry standard.

2.5.2. Simulated Distillation Analysis. The tar collected by varying the gas heat carrier temperature was dewatered and then subjected to simulated distillation. The simulated distillation curve and tar composition are shown in Figures 4 and 5.

Lignite tar was mainly composed of light components.\textsuperscript{39} Increasing the temperature of the gas heat carrier from 750 to 850 °C did not cause a significant change in the light components of the tar, with an insignificant increase from 62 to 63%. Increasing the temperature of the gas heat carrier is beneficial for increasing the content of light components in the tar. Compared with the tar collected at 750 °C, the content of light oil increased by 3.14% and the anthracene oil increased

Table 4. Fundamental Properties of Tar

| heat carrier temperature | density (g/cm\textsuperscript{3}) | water content (wt %) | ash (wt %) | toluene-insoluble content (wt %) | solidification point (°C) | flashing point (°C) |
|--------------------------|-------------------------------|---------------------|-----------|-------------------------------|------------------------|-------------------|
| 750 °C                   | 1.0569                        | 4.09                | 0.03      | 2.34                          | 29                     | 101               |
| 850 °C                   | 1.0683                        | 6.99                | 0.04      | 4.43                          | 19                     | 103               |
| YB/T 5075-2010          | ≤1.22                         | ≤4                  | ≤0.13     | ≤9                            |                        |                   |
the light oil content. Macromolecular tar reduced the asphalt content and increased the tar underwent secondary pyrolysis. The decomposition of temperature near the gas distribution chamber was high, and when the temperature of the gas heat carrier was increased, the amount of volatiles generated and the yield of tar. However, zone and enhanced lignite pyrolysis, which would increase the average pyrolysis temperature of lignite in the pyrolysis and the e effects of the heat carrier temperature and moisture in the raw material led to more eective pyrolysis and continuous, stable operation at full load for 72 h, producing high-quality tar, char, and gas.

3. CONCLUSIONS

Full-size Huolinhe lignite with various moisture contents was treated in a 30 t/d cross-flow pyrolysis device with a gas heat carrier to study the adaptability of the system to full-size lignite and the effects of the heat carrier temperature and moisture content of the raw material on the yield and properties of the pyrolysis products. Under various process conditions, this technology afforded effective pyrolysis and continuous, stable operation at full load for 72 h, producing high-quality tar, char, and gas.

(1) When the moisture of the raw material was constant, increasing the gas heat carrier temperature improved the yield of tar. When the moisture content of the raw coal was 12.49%, increasing the heat carrier temperature from 750 to 850 °C caused the Vdaf of char to decline from 10.57 to 6.59%, and the output of raw gas was reduced from 1205 to 805 Nm³/t. The heat value of gas increased from 3.88 to 4.68 MJ/Nm³, and the tar yield increased slightly to reach 81.56% of the G-K tar yield.

(2) At a constant gas heat carrier temperature, lower moisture in the raw material led to more effective pyrolysis. At 850 °C, reducing the moisture content of the raw material from 12.49 to 7.14% caused the Vdaf of char to decrease from 10.57 to 6.59%, and the output of raw gas was reduced from 1205 to 805 Nm³/t. The heat value of gas increased from 3.88 to 4.68 MJ/Nm³, and the tar yield increased slightly to reach 81.56% of the G-K tar yield.

(3) Use of the cross-flow pyrolysis moving bed afforded high-quality and high-yield tar. The content of light components exceeded 60%, and the ash content was less than 0.04%. All indexes of the tar samples obtained in the experiment were better than industry standards.

4. EXPERIMENTAL SECTION

4.1. Materials. The coal sample used in the test was dried lignite from Huolinhe City, Inner Mongolia Autonomous Region, China, obtained by drying in a rotary kiln. The drying process is not described in this study. According to the national standard, Proximate, Ultimate, and G-K analyses were carried out for the lignite samples. The results are shown in Table 5. The tar yields from G-K analyses were 6.72–6.78%.

All dry lignite samples were sieved with 1, 3, 6, 13, 25, and 50 mm sieves. The particle size distribution ranges of the raw materials after sieving are shown in Table 6. The coal particle size was mainly concentrated in the range of 3–50 mm (accounting for about 80%). The lower the total water content of the lignite samples, the higher the small particle content.

4.2. Process of the 30 t/d Pilot Plant. The overall technological process of the 30 t/d lignite pyrolysis pilot test device is shown in Figure 6, including a bucket elevator, cross-flow pyrolysis moving bed, screw discharger, dust collector, condensation tower, mist eliminator, gas pressure blower, gas incinerator, oil–water separation tank, etc.

The basic steps in the pilot test are as follows: (1) cold commissioning of the transmission devices, such as the bucket elevator, screw discharger, gas pressure blower, water pump, and so on, was carried out. (2) The pyrolysis furnace was preheated with natural gas, and the gas pressure blower and circulating condensate system were started at the same time. (3) When the temperature in the pyrolysis furnace reached the specified temperature, the bucket elevator was used to add raw materials to the pyrolysis furnace. The consumption of natural gas and air was gradually increased to increase the temperature of the gas heat carrier. The discharge speed of the screw

Table 5. Proximate, Ultimate, and G-K Analyses of Huolinhe Lignite

|   | proximate analysis (wt %) | ultimate analysis (wt %, daf) | G-K Tar (wt %, d) |
|---|---------------------------|-------------------------------|-----------------|
|   | M   | A   | Vd  | FCd | C   | H   | N   | S   | O   | Qnet /MJ·kg⁻¹ |   |
| A  | 12.49 | 20.67 | 37.57 | 40.61 | 74.42 | 4.00 | 1.12 | 0.43 | 20.03 | 15.95 | 6.72 |
| B  | 13.82 | 20.26 | 37.65 | 42.09 | 74.57 | 4.01 | 1.12 | 0.43 | 19.87 | 16.62 | 6.78 |
| C  | 7.14  | 20.51 | 37.53 | 41.96 | 74.49 | 4.00 | 1.12 | 0.43 | 19.95 | 17.29 | 6.75 |

Determined by the element mass balance.
discharger was reduced to increase the residence time of the material in the pyrolysis furnace. (4) When the gas sample after the gas pressure blower met the combustion requirements, the self-produced gas was gradually used to replace the natural gas as the heat source of the pyrolysis furnace. (5) The recycled gas consumption, air consumption, and discharge speed were adjusted, and the temperature of the gas heat carrier and the final pyrolysis temperature in the pyrolysis furnace were gradually adjusted to the target temperature. When the input, output, flow, and temperature data reached a stable state, the data and samples were collected. (6) At the end of the experiment, the flow of gas and air to the pyrolysis furnace was switched off, and the feeding and discharging speeds were increased. When the temperature in the furnace dropped below 200 °C, feeding was stopped and all the cold materials in the pyrolysis furnace were discharged.

During the test, the hot char was cooled using the gas and char condenser and then discharged from the pyrolysis furnace through the screw discharger. The discharge speed of the pyrolysis furnace was controlled by the conversion frequency of the screw discharger. The output speed was calculated from the data for the belt conveyor. The raw pyrolysis gas was passed through the dust collector, condensation tower, and mist eliminator to separate the dust, gas, and water, respectively. The gas was pressurized using a gas pressure blower and transported to the pyrolysis furnace and gas incinerator. The oil–water mixture was passed into the oil–water separation tank for separation and metering. The gas pressure blower was regulated to the outlet pressure of the raw gas and the recycled gas. The outlet pressure of the raw gas was set to 0–20 Pa to ensure that a slightly positive pressure was maintained in the pyrolysis furnace. The pressure of the recycled gas was controlled to 3000 Pa. The temperature of the gas heat carrier was controlled by the gas and air consumption. Notably, excess gas was supplied in the combustion process in order to control the temperature and oxygen content of the gas heat carrier. The combustion chamber was equipped with a heat storage structure to achieve stable combustion of low calorific value gas.

4.3. Test Cross-Flow Pyrolysis Furnace. 4.3.1. Process Principle. In this study, the vertical cross-flow pyrolysis furnace was used for the pyrolysis of the gas heat carrier; the process principle is shown in Figure 7. The cross-flow pyrolysis furnace consisted of two pyrolysis units, including two pyrolysis zones, two char cooling zones, two gas distribution chambers, and a gas collection chamber. The gas collection chamber was shared by the two pyrolysis units. The coal entered the upper part of the pyrolysis furnace, moved downward by the action of the screw discharger, and passed through the pyrolysis zone and the cooling zone successively. In the pyrolysis zone, the gas heat carrier entered the pyrolysis zone through the openings in the sidewall of the gas distribution chamber and penetrated the pyrolysis zone transversely to achieve heating and pyrolysis of lignite. These openings of the gas distribution chamber were not the same size and were determined by calculating the gas flow and temperature of the circulating cooling water. The hot gas produced in the char cooling zone entered the gas distribution chamber through the opening in the sidewall of the gas collection chamber. Further purification and dust removal were realized in the gas collection chamber. The gas was output from the gas outlet at the upper part of the gas collection chamber. In the char cooling zone, the char was cooled to below 250 °C with cool gas first and then was passed into the char cooler for further cooling to below 80 °C, which was determined by the flow and temperature of the circulating cooling water. The hot gas produced in the char cooling zone entered the gas distribution chamber and was mixed with the flue gas produced by combustion to reach the target temperature of the gas heat carrier. Finally, mixed particle lignite was treated in the pyrolysis furnace, which afforded

Figure 6. Cross-flow pyrolysis moving bed process chart, including: (1) bucket elevator, (2) cross-flow pyrolysis moving bed, (3) screw discharge, (4) belt conveyor, (5) electronic belt scale, (6) pressure gauge, (7) dust collector, (8) condensation tower, (9) mist eliminator, (10) gas pressure blower, (11) gas flowmeter, (12) gas flowmeter for recycling, (13) gas incinerator, and (14) oil–water separation tank.

Figure 7. Pyrolysis process principle of the cross-flow moving bed of the gas heat carrier.
reduced bed resistance, rapid heat transfer, and efficient dust removal.

According to the flow path and heating mode of the gas heat carrier in the pyrolysis furnace, the temperature-field distribution in the simulated pyrolysis furnace is shown in Figure 8.

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**Figure 8.** Schematic diagram of temperature field distribution in a cross-flow pyrolysis moving bed.

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### 4.3.2. Monitoring Points of Temperature

In this study, the temperature of the gas heat carrier was separately controlled with the temperature control system. The gas, air, and char cooling gas in each combustion chamber were distributed and controlled so as to regulate the heat carrier temperature in each pyrolysis unit.

The distribution of the monitoring points in the cross-flow pyrolysis moving bed is shown in Figure 9, including heat carrier temperature 1, final pyrolysis temperature 1, final pyrolysis temperature 2, heat carrier temperature 2, temperature of the lower part of the gas collection chamber, and gas outlet temperature. The area in the red box is the temperature-field measurement point in the pyrolysis area.

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**Figure 9.** Temperature monitoring points in the pyrolysis zone, including: (a) heat carrier temperature 1, (b) final pyrolysis temperature 1, (c) final pyrolysis temperature 2, (d) heat carrier temperature 2, (e) temperature of the lower part of the gas collection chamber, and (f) gas outlet temperature.

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### 4.4. Product Analysis

#### 4.4.1. Char Analysis

Proximate analysis and measurement of the calorific value were performed in accordance with the national standards GB/T212-2001 and GB/T213-2008.

#### 4.4.2. Gas Analysis

The gas samples were collected in a gas bag at the pipe behind the gas pressure blower and analyzed with an SP2100A gas chromatograph produced by the Beijing Beifen Tianpu Company. The volume fraction of each component (H₂, CH₄, CO, CO₂, C₂H₄, C₂H₆, C₃H₆, and C₃H₈) in the gas was measured. In this study, C₂H₆, C₃H₈, and C₄H₁₀ are collectively referred to as C₄H₈.

#### 4.4.3. Tar Analysis

The tar quality was measured according to the following standards: the distillation distribution of tar was measured according to NB/SH/T0558-2016, the density with GB/T2281−2008, the kinematic viscosity with GB/T265-88, the ash content with GB/T2295-2008, the moisture with GB/T2288-2008, the toluene insolubles with GB/T2292-1997, and the flash point and ignition point with GB/T3536-2008.

At the end of each experiment under the respective conditions, the tar collected in the oil−water separation tank was dehydrated and analyzed by simulated distillation to determine its fraction distribution at different boiling points. The tar fractions from high-temperature coal were divided into six fractions based on their composition: light oil (<170 °C), phenol oil (170−210 °C), naphthalene oil (210−230 °C), washing oil (230−300 °C), anthracene oil (300−360 °C), and asphalt (>360 °C); the components obtained at temperatures <360 °C are collectively referred to as light components.

Unless otherwise specified, all yields in this study are based on the mass fraction of dry coal.

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**AUTHOR INFORMATION**

### Corresponding Author

Mo Chu – School of Chemical & Environmental Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China; Email: CCCUMTB@163.com

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### Authors

Tao Fan – School of Chemical & Environmental Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China; Beijing Detianyu Investment Management Limited Liability Company, Beijing 100020, China; [orcid.org/0000-0003-1801-7903](https://orcid.org/0000-0003-1801-7903)

Zhibing Chang – School of Chemical & Environmental Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China; [orcid.org/0000-0002-3339-0020](https://orcid.org/0000-0002-3339-0020)

Complete contact information is available at: [https://pubs.acs.org/10.1021/acsomega.0c03109](https://pubs.acs.org/10.1021/acsomega.0c03109)

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### Notes

The authors declare no competing financial interest.

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ABBREVIATIONS

LR: Lurgi–Ruhrgas; Toscoal: pyrolysis technology of Toscoal Company; DG: solid heat carrier pyrolysis technology with ash from Dalian University of Technology; COED: char oil energy development; LFC: liquid from coal; GF: first-generation pyrolysis technology of Guodian Futing Company; SP: pyrolysis technology of Sanjiang Coal Chemical Industry Company; MRF: multistage rotary furnace; A750: sample A with the gas heat carrier at 750 °C; B850: sample B with the gas heat carrier at 850 °C; C850: sample C with the gas heat carrier at 850 °C

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