Technical and Benefit Evaluation of Fruit-Wood Waste Gasification Heating Coproduction of an Activated Carbon System

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ABSTRACT: Biomass gasification polygeneration technology can well address both the economic and environmental issues that impeded the development of biomass gasification technology. To further improve the utilization efficiency of biomass, preactivation of gasified carbon is realized in the gasification reactor. The aim of this study is to adopt a new gasification reactor and an environmental protection combustion chamber to obtain high value-added activated carbon with clean heating. In this paper, an experimental study on the fruit-wood waste gasification heating coproduction of an activated carbon system was carried out. The results show that the yield of gasified carbon is 20.22%, the specific surface area of gasified carbon reaches 590 m²/g, the yield of activated carbon is 10.37%, and the gas yield is 1.9 Nm³/kg. The gasification efficiency of the system is 57.83%, the energy that is transferred to the activated carbon is 18.72%, and the percentage of fixed carbon is 24.3%. Compared with the biomass particle, coal, and natural gas heating projects, the environmental protection benefits of the project are significant, and the negative emission of CO₂ is realized. Compared with the heating benefit of coal and natural gas, the economic benefit of this project is more significant.

1. INTRODUCTION

Energy is an important material basis for the survival and development of human society. However, currently, the main energy industries rely heavily on nonrenewable mineral resources, which cause serious environmental problems.¹–³ As petrochemical-based substitutes, biomass resources have attracted the attention of governments, academicians, and enterprises due to their huge quantity and renewable, clean, and low-carbon characteristics in the process of conversion and utilization. Therefore, it is very important to increase the value and the utilization of biomass resources to build a clean, low-carbon, safe, and efficient energy system.

Biomass utilization technologies mainly include direct combustion technology, thermochemical conversion technology (gasification and liquefaction), biochemical conversion technology, etc.⁴,⁵ Gasification technology is the most promising utilization technology and has wide applications (large-scale or small-scale utilization) due to its low cost and other characteristics.⁶,⁷ However, traditional biomass gasification technology only pays attention to the utilization of gasification syngas, while it does not consider biomass charcoal products in the gasification process (biomass charcoal has the potential to improve soil quality, air environment, carbon sequestration, and emission reduction).⁸ The development and application of the biomass gasification in the industry have caused long-term problems such as the generation of a single product, wastewater and residue pollution, small-scale utilization, poor continuous stability, and low economic benefits.⁹ Biomass gasification polygeneration technology is a process that uses air as a gasification agent and converts cellulose, hemicellulose, and lignin macromolecules into small-molecule biomass combustible gas, small-molecule biomass biochar,
and small-molecule liquid through a thermochemical reaction without any additional energy and additives. The main combustible components of biomass fuel gas are CO, H2, CH4, and a very small amount of CnHm (n > 1), which can be widely used in various fields of industrial and agricultural production, such as power generation, gas supply, heating (instead of coal combustion), etc. At the same time, the obtained biochar derived from fruit-wood waste and fruit shell has a developed pore structure and can be converted into activated carbon with less ash content. The liquid product is directly used as fuel for boiler heating through the burner, which solves the worldwide problem of tar and wastewater from traditional biomass gasification.

Biomass gasification polygeneration unit is mainly divided into downdraft and updraft fixed-bed gasifier. Due to its advantages of low tar content in gas, the downdraft fixed-bed gasification device is a research hotspot in the current gasification device.12−15 The downdraft fixed bed is divided into four reaction zones from top to bottom: drying zone, pyrolysis zone, oxidation zone, and reduction zone.16,17 In this study, the difference between the gasification polygeneration device and the traditional gasification device is that this device is a mixed-bed gasification device between a downsuction and an upsuction device, which uses intermediate pumping gas. A small amount of water vapor is passed into the lower part of the gas outlet to preactivate the gasified carbon. The preactivated gasification carbon is then used as the raw material of traditional activated carbon production. The gasification technology is combined with the traditional activated carbon production technology, and the preactivated gasification charcoal is used to replace the carbonization materials in activated carbon production. It greatly improves the utilization efficiency of biomass.

At present, the new gasification process has not been studied and reported by relevant scholars. In this paper, a study was conducted on the gasification heating coproduction of an activated carbon system with a heating capacity of 146 000 m2 built in Luanping, China. Then, we analyzed the system technology and the operation parameters of the system based on the 24 h operation experiment to establish the balance analysis and benefit analysis and provide the basis for the development and utilization of the project.

2. MATERIALS AND METHODS

2.1. Biomass Feedstock. About 50 tons of the fruit-wood waste from the project site was crushed to less than 50 mm. It can be seen from Table 1 that the fixed carbon and ash contents of fruit-wood waste are lower than those of an apricot shell, while the volatile content is higher than that of the apricot shell. In elemental analysis, the content of the C element in fruit-wood waste is about 4% lower than that of the apricot shell, and the content of the S element is very low. Therefore, fruit-wood waste has a certain potential of gasification and activation and is an environmentally friendly raw material.

2.2. Gasification Polygeneration System. 2.2.1. Profile of the System Construction Site. According to statistics, at the end of 2016, the total heating area in urban and rural areas in northern China in winter was about 20.6 billion m2, and the heating source was still mainly coal. The annual consumption of coal for heating was about 400 million tons of standard coal, nearly half of which was scattered burning coal with serious pollution.20 In 2017, the national ministries and commissions successively issued documents to promote the “coal to natural gas” reform, which greatly improved the air quality in northern China while also encountered a large-scale “gas panic”. The comprehensive promotion of “coal to gas” was urgently stopped by the National Development and Reform Commission (NDRC).21−23 Reducing the use of coal and improving the heat source structure are of great significance to alleviate...
the haze weather in the north and improve the environment.\textsuperscript{24} At the end of 2017, the NDRC and the energy administration on printing and distributing the guiding opinions on promoting the development of biomass heating pointed out that the green, low-carbon, and environmental protection of biomass heating is an important clean heating method and an important measure to replace coal-fired heating in counties and rural areas.

Luanping county is subordinate to Chengde City, Hebei Province, China. In 2018, the forest area of the Luanping county was 3.89 million mu. The forest biomass resources in the Luanping county are rich, and there is a large amount of fruit and wood wastes every year.\textsuperscript{25,26} Luanping is also a key area for pollution control in Beijing, Tianjin, and Hebei.\textsuperscript{27−29}

2.2.2. System Description. From November 15, 2018 to April 1, 2019 and from November 15, 2019 to March 30, 2020, the project has completed two heating seasons of full load continuous operation in the northern region (Luanping, Hebei).

The system mainly consists of five parts: feed and discharge part, new gasification reactor, boiler part, activation part, and PLC control part. The process flow is shown in Figure 1.

2.2.3. Feed and Discharge System. The fruit-wood waste is first transported to the hopper and then quantitatively sent to the gasifier by the feeding screw conveyor. The preactivated biochar is discharged from the gasification reactor by a screw conveyor with an inner water jacket.

2.2.4. New Gasification Reactor. The conical top covered at the top of the new gasification reactor is equipped with an air inlet and a spreader. The lower part of the spreader is inserted under the feeding screw, and the spreader blades rotate in the material to achieve paving and prevent bridging. The middle part of the reactor is equipped with a combustible gas extraction device to ensure that the combustible gas is uniformly drawn out. The lower part of the reactor is equipped with a rotating orifice grate to ensure that the biomass carbon falls uniformly. A steam injection device is arranged between the air extraction device and the grate device to realize the microactivation of biochar without affecting the gasification reaction. The new type of reactor is a mixed bed with intermediate pumping of combustible gas, which has the characteristics of a downdraft fixed-bed gasifier and an updraft fixed-bed gasifier. Through a small amount of spray steam, the preactivation of biomass charcoal and the upgrading of combustible gas are realized.

From the point of view of the structure, in traditional gasifiers, the gas extraction port is placed under the grate or in the upper cavity,\textsuperscript{30} and there is no separate steam injection area. The new gasifier adopts both the advantages of the upper suction gasifier and the lower suction gasifier. In principle, the new gasifier has absorbed the characteristics of the updraft fixed bed and the downsuction fixed bed. The reaction of the downsuction gasifier is completed at the upper part of the middle exhaust gas port, and the reaction of a small amount of steam and gasified carbon is completed in the lower part of the middle exhaust gas port, which not only realizes the preactivation of carbon but also increases the calorific value of gas.

2.2.5. Boiler Part. The boiler part is composed of an environmentally friendly combustion chamber and a hot water boiler system. The combustion chamber is divided into a primary cavity and a secondary cavity by a honeycomb heat storage body. The gas inlet pipe is connected to the primary cavity. The primary air pipe, ignition gun, and thermocouple are arranged on the primary cavity. The secondary air distribution pipe, thermocouple, and the secondary cavity and outlet are arranged in the secondary cavity. The flue gas pipe, the primary air pipe, the secondary air pipe, and the air volume regulating valve are connected with the air supply fan. The heat storage body solves the problem of flame instability caused by the fluctuation of the calorific value of biomass combustible gas. The temperature of the cavity is controlled by two air distribution while providing a reducing environment to reduce the nitrogen oxide content in the tail flue gas. The hot water boiler system consists of a boiler body, economizer, air preheater, and fan.

2.2.6. Activated Carbon Activation Part. The activated carbon activation part is composed of a rotary kiln body, a supporting device with retaining wheels, a kiln head, a kiln tail sealing device, and a waste heat boiler. During the slow movement of the biomass carbon from the gasifier in the rotary kiln, the temperature in the high-temperature activation section reaches 800−1000 °C. The activation stage is the preparation of activated carbon with developed micropores, which enables it with high adsorption performance. The key of the activation process is that the gas generated during this process is burned in a waste heat boiler (the boiler steam is used for the production of activated carbon) and then discharged into the atmosphere after treatment.

2.2.7. PLC Control Part. The PLC control system is realized through a control cabinet. The control cabinet includes an alarm system, buttons, and frequency modulators for all motors, as well as butterfly valves. Once the motor is overloaded, it will alarm, which can prevent the motor from burning out. The measured values of all thermocouples and pressure gauges are displayed on the control cabinet.
2.3. Experiment. The experiment was continued for 24 h. The raw material consumption, output of gasified carbon and activated carbon, as well as gas flow and calorific values were recorded once per hour. The temperature (T1, T2, T3, T4, T5, T6) and pressure (P1, P2) are shown in Figure 2. The flow rate of gas was measured by a vortex flowmeter (Beijing Shiliang) installed at the outlet of the gasification device. The heating value was measured by a calorific value analysis instrument (Wuhan Sifang) installed at the outlet of gasification equipment. Four samples of gasified carbon and activated carbon were taken for industrial analysis, elemental analysis (vario MACRO cube, Elementar, Germany), and activated carbon index analysis (IQ10 Automatic Pore Analyzer, Cantar). The exhaust gas of gas combustion was measured by a Detto350 analyzer.

The product yield is calculated by eqs 1–3, respectively

\[
g \text{gas yield (Nm}^3/\text{kg)} = \frac{\text{standard volume of gas (Nm}^3)}{\text{the mass of raw materials (kg)}} \times 100%
\]

(1)

\[
g \text{gasified carbon yield (}) = \frac{\text{the mass of gasified carbon (kg)}}{\text{the mass of raw materials (kg)}} \times 100%
\]

(2)

\[
g \text{activated carbon yield (}) = \frac{\text{the mass of activated carbon (kg)}}{\text{the mass of raw materials (kg)}} \times 100%
\]

(3)

The steam input of the preactivation module is expressed by the steam fuel ratio (SR), as shown in eq 4

\[
\text{SR} = \frac{\text{heavy of steam supplied by preactivation module}}{\text{heavy of the raw materials}}
\]

(4)

2.4. Equilibrium Analysis. 2.4.1. Energy Balance. By analyzing the enthalpy difference of the materials in and out of the device or the change of thermodynamic energy, the heat transferred in the reaction process was determined. The assumptions and related technical methods in the energy balance analysis of this study are as follows: (1) based on the 24 h operation parameters of the system; (2) the energy carried by the products in the heat calculation of the products is composed of chemical enthalpy and sensible heat, and the heat capacity of each product is regarded as a constant; and (3) the transfer of potential difference and work is ignored. From the point of view of energy balance, the system transfer balance equation is as follows (5)

\[
Q_{\text{fin}} = Q_g + Q_g + Q_{\text{ds}} \\
= Q_h + Q_{\text{ac}} + Q_{\text{dh}} + Q_{\text{d}1} + Q_{\text{d}2}
\]

(5)

Among them, \(Q_{\text{fin}}\) is the chemical energy of fruit-wood waste, kJ; \(Q_g\) is the chemical energy of gasified carbon, kJ; \(Q_g\) is the chemical energy of gas, kJ; \(Q_{\text{ds}}\) is the heat loss of the gasification preactivation device, kJ; \(Q_h\) is the heat of heating, kJ; \(Q_{\text{ac}}\) is the chemical energy of activated carbon, kJ; \(Q_{\text{dh}}\) is the heat loss of gas combustion, kJ; \(Q_{\text{d}1}\) is the heat loss of the gas boiler (0.3%); and \(Q_{\text{d}2}\) is the heat taken away from flue gas. The calculation formulas are as follows

\[
Q_{g} = m_{g} \times q_{g}
\]

where \(m_{g}\) is the yield of 24 h gasified carbon, kg; \(q_{g}\) is the low heating value of gasified carbon, kJ/kg.

\[
Q_{g} = m_{g} \times q_{g}
\]

where \(m_{g}\) is the yield of 24 h gasified carbon, kg; \(q_{g}\) is the low heating value of gasified carbon, kJ/kg.

\[
Q_{g} = V_{s} \times q_{g} \times 4.2
\]

where \(V_{s}\) is the accumulated volume of 24 h gas, Nm\(^3\); \(Q_{d}\) is the calorific value of gas, kcal/Nm\(^3\).

\[
Q_{a} = Cm \Delta t
\]

where \(C\) is 4.2 kJ/(kg·°C), \(m\) is the total mass of 24 h heating and circulating water, kg(150 t/h), and \(\Delta t\) is the temperature difference between the outlet and return water of 20 °C.

2.4.2. Carbon Balance. In this system, high value-added activated carbon products can be obtained at the same time of heating, which can not only produce substitutes for fossil energy but also have obvious greenhouse gas emission reduction benefits. Based on the experimental operation parameters of the system, the carbon balance system analysis can be a good evaluation of the system emission reduction benefits. When the system is in operation, the carbon conversion equation is as follows (6)

\[
C_{y} = C_{g} + C_{C} + C_{f} + C_{g_{c} - k} + C_{g_{c} - a}
\]

(6)

Among them, \(C_{y}\) is the amount of C in the raw material, \(C_{g}\) is the amount of C in the gasified carbon, \(C_{C}\) is the amount of C in the gas, \(C_{ac}\) is the amount of C in the activated carbon, \(C_{f}\) is the amount of C after combustion of the gas, and \(C_{g_{c} - a}\) is the amount of C in the exhaust gas after the activation of the gasification carbon.

The specific calculation formulas are as follows

\[
C_{y} = m_{\text{fin}} \times R_{C}
\]

\[
R_{C} \text{ is the mass percentage of carbon in the raw material.}
\]

\[
C_{g} = m_{g} \times C_{g}
\]

\[
C_{C} \text{ is the mass percentage of carbon in the gasified carbon.}
\]

\[
C_{ac} = m_{ac} \times G_{Ac}
\]

where \(m_{g}\) is the total mass of activated carbon in 24 h and \(m_{ac}\) is the mass percentage of carbon elements in activated carbon.

2.5. Economic Data. Economic evaluation mainly includes the estimation of total investment and benefit analysis. The total investment of the project is calculated according to the relevant national construction quota standards in 2019. The total investment mainly includes equipment investment, installation engineering investment (6% of the total investment based on site engineering construction), construction engineering investment (15% of the total investment), and other investments (8% of the total investment). In the benefit analysis, the price level is based on the price level in the first half of 2019, and the prices of raw materials and products are based on the average market prices in recent 3 years.

3. RESULTS AND DISCUSSION

3.1. Gas and Solid Yield. Figure 3 shows the yields of gasified carbon, activated carbon, and gas for 24 h. It can be seen from the figure that the yield of gasified carbon is...
maintained at 18.97−21.31%, the yield of activated carbon is maintained at 9.88−11.83%, and the gas yield is maintained at 1.78−2.01 Nm³/kg. The average yield of gasified carbon, activated carbon, and gas is 20.2%, 10.73%, and 1.9 Nm³/kg, respectively. The activated carbon yield of traditional carbonization followed by the activation preparation process is less than 10%,31 while the activated carbon yield of this process reaches 10.73%. According to the previous operation experience to meet the requirements of stable heating, the mass of steam fed into the preactivation zone is 2.8% of the raw material.

3.2. Gasification Temperature and Pressure. According to the average value of T1−T6, the temperature curve of the gasifier bed is shown in Figure 4. In the gasification process, there are several interactive reaction stages: (1) pyrolysis: the pyrolysis temperature is 295−398 °C, the position is 700−1100 mm below the flat material layer, and a large amount of volatile matter spills out; (2) oxidation: the oxidation temperature is 622−677 °C, and the position is 1100−1500 mm below the flat material layer, releasing a large amount of heat for reaction heat; (3) reduction: the stages of reduction and oxidation are interwoven; and (4) preactivation: it can be seen from the figure that it is almost connected with the cooling stage, and the temperature drops from 857 to 392 °C. This is due to the activation endothermic reaction, which is caused by the introduction of water vapor into this part, resulting in the reduction of the temperature of the gasified carbon. According to the record statistics, the average pressure drop of the gasifier is 2500 Pa.

3.3. Product Quality. 3.3.1. Gas. The composition of the producer gas and the lower heating value (LHV) are shown in Figure 5. It can be seen that the composition of gas is relatively stable through 24 h sampling analysis, and the LHV is maintained between 4.17 and 4.7 MJ/Nm³. The average LHV of gas is 4.48 MJ/Nm³. The volume fraction of hydrogen was maintained at 18.97−21.31%, the yield of activated carbon is maintained at 9.88−11.83%, and the gas yield is maintained at 1.78−2.01 Nm³/kg. The average yield of gasified carbon, activated carbon, and gas is 20.2%, 10.73%, and 1.9 Nm³/kg, respectively. The activated carbon yield of traditional carbonization followed by the activation preparation process is less than 10%,31 while the activated carbon yield of this process reaches 10.73%. According to the previous operation experience to meet the requirements of stable heating, the mass of steam fed into the preactivation zone is 2.8% of the raw material.

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maintained between 13.08 and 15.23%, with an average value of 14.29% in 24 h. It is 2–3% higher than that in conventional gasification due to the reaction of carbon and steam that produces a certain amount of hydrogen in the preactivation reaction. The average nitrogen content can be obtained by the subtraction method to be 51.42%.

3.3.2. Solid. The elemental analysis and industrial analysis of gasified carbon and activated carbon are shown in Table 2. The fixed carbon content of the gasified carbon reaches 83.50%, which can be used to make commercial activated carbon. The volatile matter (9.87%) is reserved, which can be used to supplement the heat of the activated carbon process. From the elemental analysis, it can be seen that part of sulfur is fixed in the gasification carbon. The adsorption properties of activated carbon and gasification carbon are shown in Table 3. It can be seen that the activated carbon from an apricot shell can reach the standard of commercial activated carbon (GB/T 13803.1-1999). Because the adsorption capacity of gasified carbon is more than 3 times that of traditional process carbonization material, both the activation time and the activation cost are greatly reduced.

3.3.3. Boiler Exhaust Gas. During the operation of the project, the unit tested exhaust emission values are shown in Table 4. All pollutants meet the standard requirements, and NOx is slightly higher but within limits.

3.4. Balance Analysis Based on Operating Parameters. 3.4.1. Energy Balance. According to the energy balance (see Figure 6), 57.86% of the energy is transferred to gas, 40.97% of the energy is stored in the gasified carbon, and only 1.17% of the energy is lost through the wall of the gasification reactor. During the activation process, 21.74% of the energy is transferred to the activated carbon, and 18.72% of the energy is lost in the activation reaction. The water vapor activation and carbon generated in the water–gas reaction, and the CO and H2 generated in the activation furnace were burned with the supplementary air at high temperature to provide the heat needed for the activation reaction. It also can be seen from the figure that the boiler efficiency of the project is 87.3%. Compared with the traditional gasification technology (gasification efficiency is about 80%33), the gasification efficiency of this project is much lower, only 57.86%. Similarly, the main advantage of this project technology is to seek the maximum utilization efficiency with obtaining high value-added activated carbon in the heating process.

3.4.2. Carbon Balance. Carbon balance analysis is shown in Figure 7. After gasification of fruit-wood waste, 44.6% of C is
transferred to gasified carbon, and 55.4% of C exists in CO$_2$ and transferred to gas. Gasified carbon is further activated in an activation furnace; 24.3% of C (equivalent to fixed CO$_2$) is transferred to activated carbon, and 20.3% of C exists in CO$_2$ and is transferred to flue gas during activation. Therefore, the system can reduce CO$_2$ emission by fixing carbon in activated carbon. In other words, plant growth needs to absorb CO$_2$ fixed in activated carbon from the atmosphere, which has significant environmental benefits.

### Table 5. Economic Analysis of the Project

| Serial number | Project | Amount (Ten thousand yuan RMB) | Remarks |
|---------------|---------|---------------------------------|---------|
| 1             | Total investment cost (T) | 547.00 | T = e + i + c + o (Scale: heating 146000 m$^2$) |
| 1.1           | Equipment cost (e) | 390.00 | e = g + h + a |
| 1.1.1         | Gasification (g) | 240.00 | Gasification reactor, feeding and discharging equipment, control, etc. |
| 1.1.2         | Boiler (b) | 60.00 | Boiler, combustion chamber, boiler auxiliary equipment, etc. |
| 1.1.3         | Activation part (a) | 90.00 | Activation furnace, activated carbon post-treatment device, etc. |
| 1.2           | Installation cost (i) | 32.00 | |
| 1.3           | Construction cost (c) | 82.00 | |
| 1.4           | Other expenses (o) | 43.00 | |
| 2             | Operating costs | 441.67 | Each heating season (Converted to 1 heating season (135 days)) |
| 2.1           | Fruit-wood waste costs | 330.00 | Consumption of raw materials: 5499 t, price: 600 yuan RMB/t |
| 2.2           | Labor costs | 60.75 | 3 class/day, 5 persons/class, 300 yuan RMB/day/person |
| 2.3           | Self consumption | 25.92 | 80 kwh/h, 1 yuan RMB/kwh |
| 2.4           | Maintenance fee | 20.00 | |
| 2.5           | Office expenses | 5.00 | |
| 3             | Operating income | 1012.80 | |
| 3.1           | Heating revenue | 481.80 | Heating 146000 m$^2$, 33 yuan RMB/m$^2$ |
| 3.2           | Activated carbon revenue | 531.00 | 9000 yuan RMB/t, 590 t |
| 4             | Total profit | 571.13 | |

### 3.5. Benefit Analysis

#### 3.5.1. Economic Analysis

The investment cost, operating cost, and economic benefits of the fruit-wood waste gasification and the heating coproduction-activated carbon system are the key factors affecting the implementation and application of the project. Table 5 shows the economic analysis of the heating period of this system. Figure 8 shows a comparison of the investment and income of this system with that of coal and natural gas heating. From Table 5, it can be seen that the scale of this project was
CO₂ emissions are zero during the heating process, but during the pretreatment processes such as drying, transportation, and crushing. However, coal and natural gas almost exclusively emit CO₂ in the heating process, and the emissions are 15.35 times and 12.7 times that of this system. In the utilization process of this project, the activated carbon with high added value fixes CO₂ (56 g/MJ). Therefore, this project has negative emissions and significant environmental benefits.

4. CONCLUSIONS

Based on the experiments, this paper evaluated the technical benefits of the established biomass gasification coproduction-activated carbon system. The technical characteristics of the system based on a 24 h experiment were analyzed, and balance analysis and benefit analysis based on operating parameters were also established. The following conclusions can be drawn:

1. The system innovation lies in the new gasification reactor and environmentally friendly combustion chamber. The central part of the new type gasification reactor draws out combustible gas, and the lower part of the combustible gas outlet is fed with a quantitative amount of water vapor to ensure stable gasification and at the same time preactivate the gasified carbon. The environmentally friendly combustion chamber combines the heat storage chamber and staged combustion to ensure stable combustion and environmental protection.

2. After 24 h of the full load test, 40.735 tons fruit-wood waste was consumed in the system, and the yield of gasification carbon was 20.22%. After preactivation in the gasification reactor, the specific surface area of gasified carbon reached 590 m²/g, the yield of activated carbon was 10.37%, and the yield of gas was 1.9 Nm³/kg. The gas was burned through the combustion chamber, and the exhaust gas was up to the standard, and the stable heating was 146 000 m² for urban residents.

3. Through the balance analysis and benefit analysis, the gasification efficiency of the system was 57.83%, the energy transferred to activated carbon was 18.72%, and the percentage of fixed C was 24.3%. The negative CO₂ emission of the comprehensive system was 48.213 g/MJ. Compared with biomass particle, coal, and natural heating projects, the environmental protection benefits are significant, and compared with the heating benefits of coal and natural gas, the economic benefits are remarkable.

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