Features and Commercial Performance of a System of Biomass Gasification for Simultaneous Clean Heating and Activated Carbon Production

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ABSTRACT: Biomass is a renewable and clean energy. Moreover, clean heating plays a vital role in solving issues related to the heating source structures in northern China. This paper reports on our novel technology: a system of biomass (mainly fruitwood waste, referred to in short as FWW) gasification for simultaneous clean heating and fruitwood activated carbon (FAC) production. In particular, we will discuss the features of our gasification system and product characteristics, as well as energy efficiency, environmental benefits, and economic benefits. The results showed that the energy conversion from FWW gasification was as follows: 48.10% hot gas, 49.08% fruitwood gasified carbon (FGC), and 2.82% energy loss. The NO\textsubscript{x} emissions of this system were about 126 mg/Nm\textsuperscript{3}. The iodine adsorption values of the derived FGC and FAC were about 550 and 1000 mg/g, respectively. The system of gasification consumed 36 t of FWW per day, obtained 10 t of FGC, and produced 5 t of FAC. The emissions of CO\textsubscript{2} were neutral during the operation, and the clean heating area was 4100 m\textsuperscript{2}/d in Chengde, Hebei, China, with the payback period under one heating season. These results show that the system is practical, economical, energy-saving, and environmentally friendly.

1. INTRODUCTION

Gasiﬁcation is a promising thermochemical process for the utilization of biomass in which biomass is converted into syngas consisting primarily of CO, CO\textsubscript{2}, H\textsubscript{2}, and CH\textsubscript{4}, which can be ﬂexibly used for internal combustion engines and synthesizing liquid fuels.\textsuperscript{1−5} However, an internal combustion engine is not eﬃcient and can easily break down in the presence of tar, while ash and metallic species in biomass remarkably reduce the quality of liquid fuels.\textsuperscript{6−8} Numerous studies have reported that Ni-loaded catalysts exhibit excellent performance in catalytic tar reforming,\textsuperscript{9−14} and a torrefaction pretreatment can improve the quality of the liquid fuel of biomass.\textsuperscript{15} These previous studies achieved remarkable advances in understanding catalytic tar reforming behavior and migration of oxygen and carbon during biomass torrefaction. However, it is unfortunate that the Ni-loaded catalysts can easily form coke and get deactivated,\textsuperscript{16} as well as the torrefaction pretreatment cost is high, and both of them are difficult to achieve commercialization. Moreover, wet scrubbing and electrostatic decoking are usually employed to remove tar and organic matter from combustible gases during commercialization operation.\textsuperscript{17,18} However, this will inevitably produce pollution-related problems of wastewater, volatile organic compounds (VOC), and waste residues.

The key barriers that prevent biomass gasiﬁcation technology and activated carbon production from achieving commercialization are as follows: (1) The preparation of biomass feedstock, such as collection, drying, and transportation, is signiﬁcantly expensive. (2) Biomass ﬂowability is notably poor, thus easily causing bridging and blocking issues. (3) The production of activated carbon by traditional physical methods mostly adopts the process of ﬁrst carbonization and then activation. In the process of carbonization and activation, a lot of energy is wasted, it causes environmental pollution, and an external heating source (coal burning) is also needed. (4) Finally, the purpose of traditional gasiﬁcation is to convert carbonaceous materials into gaseous products as completely as possible, so that the carbon residue is extremely low, but it produces slag and tar, which results in overall poor economical and environmental benefits.

Received: August 1, 2020
Accepted: September 18, 2020
Published: October 1, 2020
Recently, biochar as a tar reforming catalyst has become a research hotspot. However, it is difficult to recycle “green” biochar in a gasification reactor. It has recently been proposed that the gasification concept can change. For example, the acceptance of char production can not only ease the experimental conditions but also make char a valuable product, favoring its commercialization. Simultaneously, the combustible gas containing tar is burned by low-nitrogen environmental protection technology, which can not only solve the problem of tar and wastewater pollution but also improve heating source structures used for heating, so that the residents of northern China can get rid of the heating mode that is completely dependent on nonrenewable energy sources such as coal and natural gas in cold winters. Barriers 1−3 can be solved by building a plant at a biomass-rich place, using a particularly designed gasifier, and employing biomass gasification for clean heating and production of activated carbon, respectively.

Until now, there have been few reports on economic and reliable biomass gasification systems for clean heating and production of activated carbon employing particularly designed gasifiers and low-nitrogen environmental protection technology at commercial scales. In this work, employing FWW as a raw material for gasification, clean heating and production of activated carbon, as well as the characteristics of technologies, product characteristics, energy efficiency, environmental benefits, and commercial performance, were discussed. This gasification system provided a novel route for promoting the development of biomass gasification technology.

2. GASIFICATION SYSTEM AND ITS KEY FEATURES

2.1. Site Introduction of the Gasification System. Luanping County, which is located in Chengde City, Hebei Province, China, has cold winters (the coldest ones have a temperature even lower than −20°C) and long summers (from November 1 to April 1 of the following year, up to 5 months). As of 2018, Luanping County has a forest area of 3.89 million mu, and a large amount of FWW with high moisture content and large size is produced every year. Simultaneously, Luanping is also a key area for pollution control in the Beijing−Tianjin−Hebei region of China.

2.2. Gasification Reactor. The key part of the gasification system is the gasifier where the FWW produces a hot gas (combustible gas) and FGC by thermochemical reactions. The safety, reliability, and product distribution of the gasifier strongly depend on the internal design of the gasifier. To
convert FWW with high moisture and large size into the hot gas and FGC, our gasifier was designed and manufactured with the characteristics presented in Figure 1.

2.2.1. Adapting to the High Water Content of Feedstock. Different from a common gasifier that adapts to low water content (≤20%) of biomass, our gasifier was composed of a rectangular parallelepiped furnace lined with high-temperature refractory heat storage bricks. With air as the gasification agent, the feedstock and biochar will have a violent oxidative exothermic reaction in the oxidation zone, and the heat will be absorbed by the high-temperature refractory heat storage brick body, which could be used for drying and pyrolysis of the upper biomass through conduction. Therefore, the gasifier could adapt to feedstock with higher moisture content (40%).

2.2.2. Preventing Bridging and Blocking Issues and Adapting to Large-Size Feedstock. On the top of the gasifier, there is a horizontal bar that could rotate, evenly distributing the feedstock (large size with 0.5–10 cm) around the gasifier. Simultaneously, the bar could move up and down to detect the level of feedstock inside the reactor, thereby adjusting the feed rate of feedstock.

2.2.3. Gasification Process Design. As presented in Figure 1a, air was introduced as a gasification agent at the top of the gasifier to gasify the biomass. At this stage, the air supply was regulated strongly and carefully to avoid unexpected temperature rise. Then, the premixed air and steam were supplied to the middle area of the gasifier to gasify and microactivate the biochar. It is a proven fact that diluting air with steam is an effective way to control the reaction temperature. Subsequently, the biochar reacted with steam for further activation and was allowed to cool down before entering the discharge area.

2.2.4. Gasified Carbon Production. In traditional gasifier, the gas and solid phases on the surface of the feedstock are under a positive pressure, making the tar produced on the surface incompletely volatilized and the pores of the biochar are either hard to form or blocked. Our gasifier uses a restrictive oxygen supply, which has the effect of activating the pores. Simultaneously, the hot gas produced is successively pumped out, resulting in a small negative pressure on the surface of the feedstock, which is in favor of the decomposition of biomass to a certain extent. Moreover, the water generated in the process of biomass pyrolysis and gasification reacts with carbon in the form of water vapor at a high temperature to microactivate the biochar. Both are in favor of the formation of gasification carbon pores. These are the reasons for the fact that the iodine adsorption value of the gasified carbon produced by our gasifier is significantly higher than that of the biochar prepared by other gasifiers. The gasified carbon with developed pores could prone process into activated carbon with an iodine adsorption value of 1100 mg/g.

2.3. Key Features of the Gasification System. Compared with traditional biomass gasification, our new technology has the following advantages:

1. It could adapt to a high water rate and large-size feedstock, and the quality of gasified carbon and activated carbon is good. A detailed reason is provided in Section 2.2 of this work;

2. As mentioned before, one of the barriers to biomass gasification technology and activated carbon production is the formation of tar. We employ a low-nitrogen, environmentally friendly, and stable combustion technology, and the hot gas containing tar and other organic matter is directed as fuel for boiler combustion and heating water. In addition, the use of a two-stage combustion unit considerably improves the environmental performance of the gasification system (the N-containing species in the volatiles are generally oxidized into NO\textsubscript{x} and are emitted into the environment in a conventional combustion system,\textsuperscript{16} polluting the air). In the first-stage combustion unit, the hot gas is partially burned under relatively low temperature and oxygen-deficient conditions, thereby promoting the formation of N\textsubscript{2} and suppressing the production of NO\textsubscript{x}. Subsequently, the remaining organic compounds are further burned in the second-stage combustion unit. The NO\textsubscript{x} emission from this gasification system is as low as around 126 mg/Nm\textsuperscript{3}, compared to about 250 mg/Nm\textsuperscript{3} from a one-stage combustion unit.\textsuperscript{16} Simultaneously, the waste heat in the exhaust gas is recycled to generate hot air and sent to the gasifier, thereby effectively improving the overall energy efficiency. Moreover, the controller is connected to the thermocouple and air volume control valve of the two-stage combustion unit as well as to the air blower, and so on, to control the stable combustion of the hot gas.

2.4. Gasification System for Clean Heating and Production of Activated Carbon. As presented in Figure 2, the FWW was sent to the gasifier through a hoist and gasified at temperatures in the range of 600–800 °C for about...
and the LHV of the hot gas was generally over 4.5 MJ/Nm³.

Subsequently, the FGC was activated under steam for about 5 h, which could produce about 0.14 t of FAC.

Activated carbon, respectively.

The hot gas output of the system was about 1.87 Nm³/kg, and the LHV of the hot gas was generally over 4.5 MJ/Nm³. The stability of the system’s hot gas was also well manifested by the trendline in Figure 3, although reasonable fluctuation of the system resulting from the inconstant feeding rate, heterogeneous nature of biomass, and pressure was also observed.

3. RESULTS AND DISCUSSION

The commercial system has currently been in operation for 2 years, and we performed random sampling, testing, and analysis of the products of this commercial system operation for 8 consecutive days in 2019. The results are as follows.

3.1. Fuel Properties of FWW, FGC, and FAC. The proximate analysis of the samples was performed according to the Chinese National Standards GB/T28731-2012. The ultimate analysis and HHV of the samples were determined using an elemental analyzer (vario MACRO cube, Elementar, Germany) and an automatic calorimeter (ZDHW-300A, Hebei Keda Company, China), respectively.

Table 1 lists the fuel properties of FWW, FGC, and FAC. Compared to FWW, FGC and FAC have increased levels of fixed carbon content, C content, and HHV, as well as N content; from this, we can infer that the C and N elements can be fixed during the operation of the entire system. Meanwhile, the S content has no significant difference, indicating that the processes of gasification and activation and the environmental benefits were good. Moreover, the HHV of FWW was higher than those of biomass pellets,22 corn stalk,15 and palm kernel,23 indicating that FWW is a high-quality biomass energy source.

3.2. Composition and Low Heating Value of Hot Gas. Figure 3 exhibits the composition and the low heating value (LHV) of the hot gas during the 8-day examination period in 2019.

The hot gas output of the system was about 1.87 Nm³/kg, and the LHV of the hot gas was generally over 4.5 MJ/Nm³. The stability of the system’s hot gas was also well manifested by the trendline in Figure 3, although reasonable fluctuation of the system resulting from the inconstant feeding rate, heterogeneous nature of biomass, and pressure was also observed.

3.3. Composition of Boiler Exhaust. Boiler exhaust emissions are a key metric for evaluating whether a system has achieved clean production. Table 2 shows that the boiler exhaust component concentrations in the system are far lower than the boiler air pollutant emission standard values.24 Besides, the emissions of CO₂ are neutral during the system operation. Therefore, it has excellent environmental benefits.

3.4. Adsorption Properties of FGC and FAC. The adsorption values of iodine and methylene blue were measured according to the Chinese National Standards GB/T17664-1999. The surface area of the sample was determined by the adsorption of N₂ at 77 K using an automatic surface area and pore size analyzer, Q10 automatic analyzer (Quantachrome Corporation, Boynton Beach). Before the analysis, the sample was degassed at 300 °C for 900 min under vacuum. Brunauer–Emmett–Teller (BET) theory was used to calculate the specific surface area.

Non-carbon elements are decomposed from the raw material during the pyrolysis and gasification processes, so that the biochar has a certain specific surface area and pores.25 Besides, the adsorption values of methylene blue and iodine indicate the degree of development of mesoporous and microporous activated carbon, respectively. Table 3 lists the BET surface area, iodine adsorption value, and methylene blue adsorption value of FAC, which are about 950 m²/g, 1000 mg/g, and 150 mL/g, respectively. Moreover, the surface area of FGC is more than those of other biochar samples such as fiberboard biochar,26 rice straw biochar,27 and switchgrass biochar.28 Currently, the yield of FAC from this biomass gasification system in China is ~39% that of the traditional activated carbon production process.

3.5. Energy Converting Flow, CO₂ Emission, and Economic Benefits of the System. 3.5.1. Energy Converting Flow of the System. Figure 4 shows the energy converting flow of the system.
flow of the system using FWW as feedstock. This was done by using the equation $R = \text{HHV}_\text{f} / \text{HHV}_0 \times K$, where $R$ represents the energy yield (%); HHV$_f$ and HHV$_0$ represent the calorific value of FWW (MJ/kg) and the calorific value of the products (MJ/kg), respectively; and $K$ represents the yield of the products (%). Through the gasification reaction, 48.10% of the biomass energy was converted into the hot gas and 49.08% of the biomass energy was still stored in FGC, while the remaining 2.82% was lost in the form of energy loss. Subsequently, the energy converting efficiency from the hot gas to town heating was about 85.00%, while the energy converting efficiency from FGC to FAC was about 51.33%.

3.5.2. Performance of CO$_2$ Emission. The remarkable environmental performance is presented in Figure 5.

First, 1.72 t of carbon dioxide is absorbed from the atmosphere to form 1.0 t of FWW containing 47% C. After the FWW is gasified, 0.84 t of carbon dioxide (0.23 t C) is released into the atmosphere and 0.24 t of C is converted into FGC. Subsequently, the FGC is further activated by the rotary furnace, where 0.12 t of C is transferred into FAC and 0.44 t of carbon dioxide (0.12 t of C) is released into the atmosphere. Therefore, after 1.0 t of FWW is gasified for clean heating and production of FAC, 0.44 t of carbon dioxide in the air is fixed into FAC, making the system act as a carbon dioxide absorber.

3.5.3. Economic Benefits of This System. The economic benefits of the system are the key factors that determine its user’s applicability. Table 4 shows the payback period of the system investment under one heating period. Therefore, this system has zero cost for clean heating and has outstanding economic benefits.

| number | project                          | price (dollar) |
|-------|----------------------------------|----------------|
| 1     | cost of investment               | $9.28 \times 10^3$ |
|       | total system investment          | $3.43 \times 10^4$ |
|       | gasification investment          | $8.57 \times 10^4$ |
|       | boiler investment                | $2.14 \times 10^4$ |
|       | activation investment            | $2.14 \times 10^4$ |
|       | infrastructure investment        | $1.43 \times 10^4$ |
| 2     | operating expenses               |                |
|       | total expenditure                | $5.64 \times 10^3$ |
|       | FWW                             | $4.04 \times 10^3$ |
|       | labor cost                       | $8.71 \times 10^3$ |
|       | electricity cost                 | $3.71 \times 10^3$ |
|       | maintenance fees                 | $2.85 \times 10^3$ |
|       | office expenses                  | $7.14 \times 10^3$ |
| 3     | operating income                |                |
|       | total income                     | $1.69 \times 10^3$ |
|       | heating income                   | $6.88 \times 10^3$ |
|       | activated carbon income          | $1.00 \times 10^3$ |
| 4     | total profit                     | $1.98 \times 10^3$ |
| 5     | investment payback period        | under one heating season |

4. CONCLUSIONS

A system of biomass gasification for clean heating and production of activated carbon has been commercialized in Chengde, China. With the internal structure of the gasification reactor, the combustion unit, and the boiler system particularly designed, the system can successfully operate for 2 years without major maintenance. The difference from other gasification technologies is that this system not only produces hot gas for heating but also produces gasified carbon while avoiding the problems of difficult tar treatment and NO$_x$ air pollution. Besides, activated carbon, as one of the considerable products of this technology, has significant advantages in terms of economic feasibility, and part of the gasified carbon could act as a catalyst carrier in the gasification reactor. Overall, the whole system fixes carbon dioxide into activated carbon.

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Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
This work was supported by the National Promotion Project of China (No. 2020133136) and the National Natural Science Foundation of China (1776100).

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