Fuel 220 (2018) 210–219

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Development of an ultra-small biomass gasification and power generation system: Part 2. Gasification characteristics of carbonized pellets/briquettes in a pilot-scale updraft fixed bed gasifier

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ARTICLE INFO

Keywords:
Carbonized pellets
Carbonized briquettes
Updraft fixed bed gasifiers
Tar removal
Gas engine

ABSTRACT

Ultra-small biomass gasification and power generation systems are a promising technology for disaster areas in developed countries and non-electrified rural areas of developing countries. The gasification characteristics of carbonized wood pellets and carbonized wood briquettes without or with 1 wt% sea salt were tested in a pilot-scale updraft fixed-bed gasifier. The results showed that the carbon balance during gasification was easily achieved, and most of the chlorine in the carbonized briquettes with sea salt remained in the residual char and fly ash after gasification. Inorganic chlorine in the solid fuel was transformed into organic chlorine combined with carbon matrix after heat treatment in the gasifier. Syngas with a low heating value higher than 4 MJ·m^{-3} could be continuously obtained when the system reached a stable condition, which enabled power generation using a gas engine. A combination of several secondary tar removal processes was adopted for the syngas purification. The tar content in the syngas after the gas cleaning for 425 °C-carbonized pellet, 425 °C-carbonized briquette, 475 °C-carbonized briquette, and 475 °C-carbonized briquette with sea salt was 0.98, 0.26, 1.4, and 0.2 g·Nm^{-3}, respectively. During the stable stage, 425 °C-carbonized pellet showed the highest cold gas efficiency (CGE) of 45.6% and carbon conversion efficiency (CCE) of 57.8%, respectively, with an equivalence ratio (ER) of 0.24. A lower carbonization temperature showed a higher CGE and CCE. The residual char and fly ash after gasification could be considered for reuse as feedstock to further improve the overall process efficiency. The maximum output power was 23 kW at an air flow rate of 40 Nm^3/h during the gasification of carbonized pellets, and the corresponding overall power generation efficiency of the engine using the syngas was about 27.8%. For 475 °C carbonized briquette, the maximum output power was 18 kW at an air flow rate of 40 Nm^3/h, and the corresponding overall power generation efficiency of the engine using the syngas was about 25.5%.

1. Introduction

With the dramatic increase in the consumption of fossil fuels and growing serious environmental issues, ultra-small and distributed power generation technologies based on biomass gasification may be paid increased attention and extensive application in disaster areas in developed countries and the non-electrified rural areas of developing countries.

Updraft/downdraft fixed-bed gasifiers will be the most appropriate technology for realizing portable and distributed gasification and power generation. Many researchers have been engaged in studying the gasification characteristics of various kinds of biomass and the corresponding pellets/briquettes after densification using these two kinds of gasifiers [1–10]. Chen et al. tested the gasification of mesquite and juniper wood samples in an updraft fixed-bed gasifier. They concluded that there was an optimal particle size range of 4–6 mm for both raw wood materials in order to obtain the high carbon conversion efficiency (CCE) and low energy consumption required for grinding wood chips [1]. Galindo et al. proposed a downdraft gasifier with a two-stage air supply for raw wood gasification, and their gasifier could significantly decrease the tar content in the syngas owing to a temperatures increase in the pyrolysis and combustion regions [2]. Wood chip gasification in an air-blown downdraft gasifier was explored by Romar et al. [3]. The tar concentration levels were in the range of 200–400 mg·Nm^{-3}, which was similar to the data in Ref. [4]. Besides the cold gas efficiency (CGE) and carbon conversion efficiency (CCE), the compositions and heating values of the syngas and the temperature distributions inside the gasifier were also discussed in depth by some other researchers [5–10].

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https://doi.org/10.1016/j.fuel.2018.01.080
Received 20 October 2017; Received in revised form 18 January 2018; Accepted 22 January 2018
0016-2361/

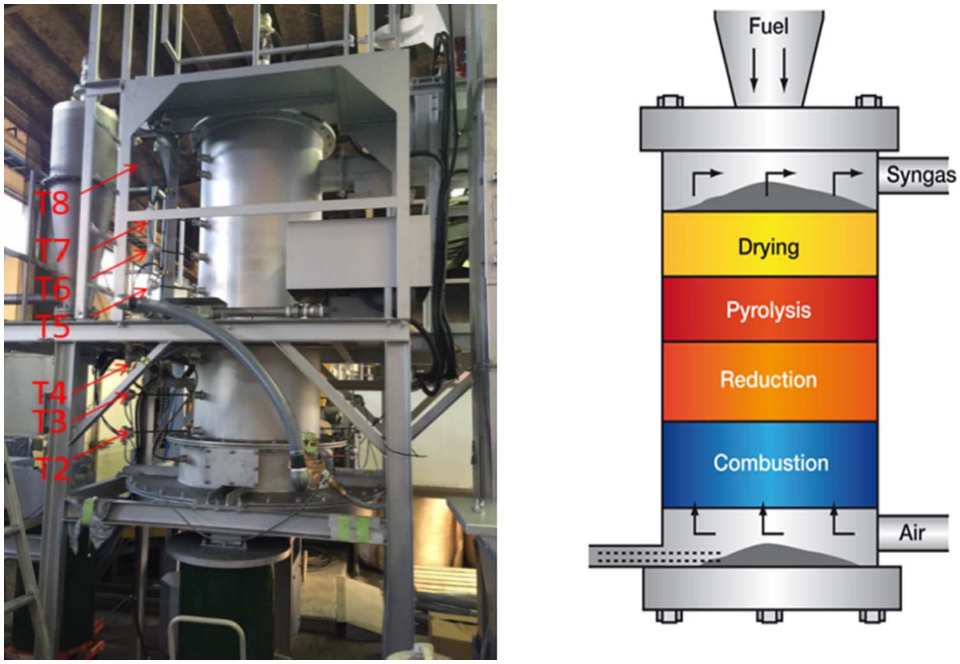

Fig. 1. The photo and schematic diagram for different reaction zones in the updraft gasifier.

Raw biomass always contains a high water content (20–60 wt%) and will produce syngas with high tar concentrations when directly applied in gasification. It is reported that the tar content in syngas should be lower than 0.1 g·Nm^{-3} for the safe operation of internal combustion engines [11,12]. Using fresh biomass as gasification feedstock increases the load on a syngas purification system. In order to overcome unfavorable factors caused by water and tar issues, some researchers have explored the gasification application using torrefied or carbonized biomass [13–16]. Kuo et al. simulated the gasification performances of raw and torrefied bamboo in a downdraft fixed-bed gasifier. The effects of the equivalence ratio (ER) and steam supply ratio on the syngas yield and quality, CGE, and CCE were evaluated, and the optimal feed conditions for gasification were predicted [13]. Deng et al. torrefied rice straw and rape stalks for their co-gasification of coal. They mention that the properties of the torrefied agricultural residues are closer to those of coal, so torrefaction is a promising method for co-gasification [14]. Actually, the hydrophobicity and uniform characters of the biomass can also be significantly improved after the torrefaction or carbonization pretreatments [17–19]. These two processes reduce the O/C ratio and improve the energy density of the biomass, which is favorable for the thermal application of the solid fuels [20]. Compared with carbonization at temperatures higher than 400 °C, biomass torrefaction always finishes within the lower temperature range of 200–350 °C [21,22]. Therefore, more volatile matter remained in the torrefaction char than in the carbonization char. This led to a higher syngas production rate by using the torrefaction char as gasification feedstock, whereas the corresponding tar content in the syngas would also increase by using torrefaction char produced at a lower thermal treatment temperature.

So far, most of the devices for torrefaction or carbonization are mainly based on electrical heating [23,24,19]. In a commercial chemical plant, there is a great amount of hot exhaust gas, which can be utilized to reduce the energy consumed in torrefaction or carbonization. However, electrical heating or the utilization of waste heat from a big factory is very difficult to achieve in a power-starved disaster zone or remote area. In our system, the carbonization furnace was based on non-electric heating, wherein the entire system was heated using the combustion heat from volatile matter in the waste wood, which might be the most appropriate way to achieve portability in the open field [25]. The one-batch capacity of the carbonization system was about 80–100 kg of dry wood, and the size of wood block used was usually about 15 cm × 8 cm × 5 cm. It was noted that most of the wood block remained uncarbonized over the torrefaction temperature range. The uncarbonized wood and half-carbonized wood char were very difficult to crush when the carbonization temperature was lower than 400 °C; therefore, the wood block was carbonized within 400–500 °C to enable crushing and densification.

As the carbonized wood char was in a low energy density and loose state, unfavorable situations such as hot-points or channeling occurred easily when fresh char was fed directly into the gasifier as bed material. Therefore, high-strength carbonized pellets or carbonized briquettes were prepared as gasification feedstock using a pelletizer or briquetter so as to ensure stable operation of the gasifier. An updraft fixed-bed gasifier may be the most appropriate fixed-bed type to realize the desired portability and distributed character. This is because the temperature of syngas from the outlet of an updraft fixed-bed gasifier is much lower than that of the downdraft type [26], which could significantly reduce the size of the cooling system. Also, the operation of an updraft fixed-bed gasifier is much easier than other types of gasifiers.

So far, most small-scale and distributed biomass gasification power generation systems are based on the utilization of raw biomass or charcoal [27–32]. To the best of our knowledge, there are no published papers on pilot-scale gasification based on carbonized biomass pellets/briquettes. In our study, biomass was first carbonized and then densified into carbonized pellets/briquettes for the corresponding gasification process. In certain areas of Japan, waste wood resources are sometimes soaked in seawater after a tsunami, so it is necessary to explore the effects of the salt from seawater on biomass gasification performance. Moreover, the release characteristic of chlorine is also a key point, considering the associated erosion issues during gasification. Therefore, besides carbonized pellets/briquettes, carbonized briquettes mixed with 1 wt% sea salt were also investigated for gasification. The cold gas efficiency, carbon conversion and balance, and residual char characteristics were evaluated. Also, the tar removal efficiency using several physical separation devices was also discussed considering the requirements of the gas engine. Finally, the performance of the gas engine was reported.