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RESEARCH

Mobile power generation system based on biomass gasification

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Abstract

Disaster-hit and/or un-electrified remote areas usually have electricity accessibility issues and an abundance of plant-derived debris and wood from destroyed wooden structures; this can be potentially addressed by employing a decentralized ultra-small biomass-fed gasification power generating system. This paper presents an assessment of the technical viability of an ultra-small gasification system that utilizes densified carbonized wood pellets/briquettes. The setup was run continuously for 100 h. A variety of biomass was densified and carbonized by harnessing fugitive heat sources before charging into the reactor. Carbonized briquettes and furnished blends exhibited inferior gasification performance compared to the carbonized pellets. In the absence of tar blockage problems, steady-state conditions were achieved when pre-treated feedstock was used. Under steady-state conditions for carbonized pellets gasification operated at an equivalence ratio of 0.32, cold gas efficiency and carbon conversion achieved 49.2% and 70.5%, respectively. Overall efficiency and maximum power output of 20.3% and 21 kW were realised, respectively. It was found that the system could keep stable while the low heating valve of syngas was over 4 MJ/m^3 on condition that avoiding tar blocking issues. The results indicate that the proposed compact ultra-small power generation system is a technically feasible approach to remedy power shortage challenge. In addition, process simulation considering carbonized wood gasification combined power generation was formulated to produce syngas and electricity. Woody pellets with the flow rate of 20 kg/h could generate a 15.18 kW power at the air flow rate of 40 Nm^3/h, which is in a good agreement with 15 kW in the 100 h operation. It is indicated that the gasification combined power generation cycle simulated by Aspen simulator could achieve reliable data to assist the complicated experiment operation.

Keywords Small-scale power generation · Densification · Carbonized pellet · Carbonized briquette · Gasification

1 Introduction

In Japan, woody biomass from forest resources is abundant as a potential candidate for enabling independent energy production in the open-field. Moreover, there are many damaged houses built by wood after earthquake or tsunami disasters. How to efficiently utilize such kind of waste wood has also got more attentions. Through the work of many researchers, it was found that thermal application through gasification can be applied as an efficient recycling means (Aljbour and Kawamoto 2013; Chen et al. 2012; Ogi et al. 2016; Ismail et al. 2020; Zheng et al. 2021; He et al. 2020). From the reference of coal gasification process developed in 18–19 centuries, biomass gasification presents nowadays as a versatile and promising way to utilize various kinds of biomass sources (e.g., forest, municipal and agricultural wastes) (Susastriawan et al. 2017;

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Shahbaz et al. 2017; Sansaniwal et al. 2017; Lythcke-Jørgensen et al. 2017; Ismail and El-Salam 2017; Heidenreich and Foscolo 2015; Pereira et al.2012). If found technically and financially feasible, biomass gasification has the potential to increase the deployment and adoption of renewables, which will augment the sustainable production of chemicals and syngas utilized in internal combustion engines for power generation (Wang et al.2016; Chaves et al.2016; Ruiz et al.2013; Yoon et al.2012; Martínez et al.2012; Son et al. 2011; Sharma 2011; Bridgwater 1995; Rajvanshi and Joshi 1989).

In the development of technology, it is a standard procedure to attempt a successful and optimized operation of miniaturized systems before commercial-scale development; biomass and/or waste gasification is no exception. The demand for cheap, agile biomass power generation systems is high, especially in disaster-prone areas like coastal Japan and areas with an abundance of biomass but no accessibility to the national electricity grid. For this reason, at least in the past 2 decades, research has been focused on the development of small-scale distributed power generation systems that utilize waste and/or biomass (Susastriawan et al. 2017; Chaves et al. 2016; Yoon et al. 2012; Mohammed et al. 2014). The need for these technologies cannot be overemphasized. The power production based on biomass gasification usually involves four main steps: biomass pretreatment, gasification, syngas purification and power generation. Gasification and power generation processes employing a fixed-bed (downdraft/updraft fixed bed) gasifier should be the most appropriate for realizing distributed characteristics. Martínez et al. (2012) made a detailed review on the biomass gasification in downdraft gasifiers and the application of syngas coupled with internal combustion engines. Various raw biomasses including wood, sawdust, rice husk, and hazelnut shells were applied for gasification and power generation tests (Mursito et al. 2020; Digman et al. 2009; Li et al.2020; Corella and Toledo 2001; Beenackers 1999). Updraft gasifier is characterized by higher efficiency and is flexible towards feedstock, compared to the downdraft gasifier. The hydrogen to carbon monoxide ratio is the decisive parameter for determining syngas quality. Cerone et al. evaluated syngas composition at different heights of the reactive biomass bed in a pilot plant operating in a continuous mode, i.e. 20–30 kg/h of biomass feed (Cerone et al. 2020). The use of steam positively affected the molar ratio of hydrogen to carbon monoxide that reached a steady value of 0.77 during the gasification operated at steam to biomass ratio of 0.11 kg/kg, versus the value of 0.46 measured in the corresponding test operated only with air. On the other hand, steam addition increased tar production up to 163 g/kg in air/steam gasification compared to the 137 g/kg with air gasification. The staged fixed-bed gasifier described by Kurkela E et al. targets a size range of 10–50 MW of feedstock input (Kurkela et al. 2021). The primary gasification stage occurs in an updraft fixed bed. The tar-containing updraft gas is further processed in the secondary gasification zone, where gas temperature is raised from 200 to 500 °C to 750–900 °C by feeding secondary oxygen through a specially designed catalytic distributor zone. Higher operation temperatures and/or a third catalyst stage would be needed in the case of agro biomass and waste feedstocks, which have higher sulfur contents. Cavalli et al. pointed out that three catalysts are compared for reforming 40 g/Nm^3 acetic acid as main primary tar compound from biomass updraft gasification using simulated bio syngas as gas carrier (Cavalli et al. 2021). The metal-based catalyst was a commercially available catalyst called TARGET™ developed specifically for tar reforming and consisted of Pt/MNS (MgO, NiO, and SiO_2) out-performed the naturally-occurring catalysts by completely converting acetic acid with almost no carbonaceous deposits accumulation. These results are expected to help the further development of tar reformers, and the commercialization of biomass updraft gasifiers based systems. Ochnio et al. examined impact of biochar and ash outflow during the updraft gasification process on the parameters of the latter (Ochnio et al. 2020). Calorific values were ranging between 6.7 and 7.4 MJ/Nm^3. Gas yield (from 1.16 to 0.94 Nm^3/kg fuel) and cold gas efficiency (from 44.4% to 40.2%) decreased. The fuel-to-tar conversion ratio (from 0.14 to 0.10) decreased along with an increase in biochar outflow.

Through the operation experiences of downdraft gasifiers, it is noted that this type of gasifier presented higher demand on the characteristics of gasifying materials such as the upper limitation of water content in fuel (≤ 25 wt%), and uniform size of materials for appropriate temperature distribution and solid–gas contact inside the gasifier. Actually, due to the natural characteristics of low energy density and strong water absorption capacity, some pretreatments to convert biomass resources with various moisture contents and shapes into uniform fuel are essential. Moreover, as a result of high exit temperature of syngas from a downdraft gasifier, it has a low gasification efficiency. While for updraft gasifier, the outlet temperature of syngas is much lower, and thus can significantly decrease the size of the cooling device and the capital cost, which is very important for reducing the size of the whole system. The most challenging issue of updraft gasifier is the high tar content in syngas when using raw biomass as a feedstock. In order to overcome this issue, raw biomass firstly experienced an almost energy-free carbonization process at 400–500 °C in our process. The carbonized char was always in low density and with uneven particle sizes, which is still not favorable for keeping stable chemical reactions in the gasifier resulting in the channeling phenomena. Previous works demonstrated that the stable operation of downdraft or updraft fixed bed gasification reactors could be achieved when densified biomass was used as a feedstock; conversely, fine biomass showed erratic behavior. Extensive research on the production of high-performance raw biomass pellets/briquettes has been reported in the literature (Whittaker and Shield 2017; Soleimani et al. 2017; Rahaman and Salam 2017; Yank et al. 2016; Kaliyan and Vance 2009). However, later researchers employed torrefaction (200–300 °C) and low temperature (350–500 °C) carbonization to enhance the fuel performances further (Yue et al. 2017; Colin et al. 2017; Bach and Skreiberg 2016; Özçimen and Ersoy-Meriçboyu 2010; Demirbaş 2001), as such, combined densification and torrefaction/carbonization are currently a widely accepted biomass pre-treatment protocol (Larsson et al. 2013; Rudolfsson et al. 2015, 2017; Bergman 2005; Hu et al. 2016). Many binders including representative organic binders, such as lignin and starch (Peng et al. 2015; Hu et al. 2015; Kong et al. 2013), as well as the inorganic binders, such as calcium chloride ($CaCl_2$), calcium oxide (CaO), $Ca(OH)_2$ and NaOH (Hu et al. 2015; Kong et al. 2013) have been explored for biomass pelletization/briquetting. Typically, binders containing alkali and alkaline earth metals (AAEMs) and chlorine are avoided as they result in ash-related issues, which include and are not limited to slagging and alkaline-induced corrosion accelerated by the presence of chloride anions. In our project, several environment-friendly binders were adopted for making carbonized pellets or briquettes. Poval, corn starch, and syrup were tried, respectively, for making high quality carbonized briquettes. Bio-oil was also added at a certain ratio when making briquettes or pellets for further optimizing the densification process.

For syngas purification, secondary clean devices including a cyclone separator, a water scrubber, a bio-oil separation centrifuge, an oil scrubber (vegetable oil and waste-cooking oil scrubbers), a char filter and a cloth filter are frequently adopted to remove heavy and light tars in syngas (Anis and Zainal 2011; Paethanom et al. 2012; Ozturl and Yilmaz 2006; Liu et al. 2011; Paethanom and Yoshikawa 2012). Different combinations of secondary purification devices were studied by Nakamura et al. (2016) and the conclusion is that 98% of tar was eliminated by the combination of some secondary devices including a bio-oil scrubber, a centrifuge and a char filter. In our project, the tar removal efficiency by combining different sets of purification devices was also investigated combined with the updraft fixed bed gasification process.

In our previous studies, the optimization of biomass pretreatment processes including carbonization and densification, and gasification characteristics of carbonized pellets and carbonized briquettes were detailed discussed (Ding et al. 2017, 2018). This paper reported the performance of a distributed power generation system based on carbonized and densified biomass gasification through the 100 hours' continuous operation in the open field. Process modelling is a favorable option to study the characteristics of gasification process, which can reduce time and capital costs consumed significantly (Kombe et al. 2022; Vikram et al. 2022). With the advantage of flexibility (Vikram et al. 2022) and accuracy (Singh and Tirkey 2021, 2022), process modelling is widely employed to investigate the sensitivity of parameters in the gasification area (Vikram et al. 2022; Singh and Tirkey 2021, 2022; Singh et al. 2022; Lan et al. 2018). In this work, a gasification combined power generation process was proposed to study the feasibility of gasification and power generation with carbonized wood, and the process modelling was carried out and compared to the pilot plant operation data. The effectiveness and applicability of our technology and the current issues were discussed, and the optimizations of the whole system were discussed for further verification of the feasibility of this new technical route for environmental-friendly small-scale power generation. In this mobile biomass gasification and power generation system, roughly 60 kg/h raw wood could maintain 30 kWh power generation, which can support around 15 persons electricity requirements.

2 Description of the integrated carbonized biomass gasification and power generation system

In this study, the system is designed for enabling independent energy production from various kinds of biomass resources in the open-field. The whole process is mainly consisted of two processes: biomass and waste pretreatment; and gasification and power generation. The first process includes carbonization, densification (briquetting or pelletization), and the second process is composed of updraft fixed bed gasification of carbonized pellets/briquettes, syngas purification and power generation.

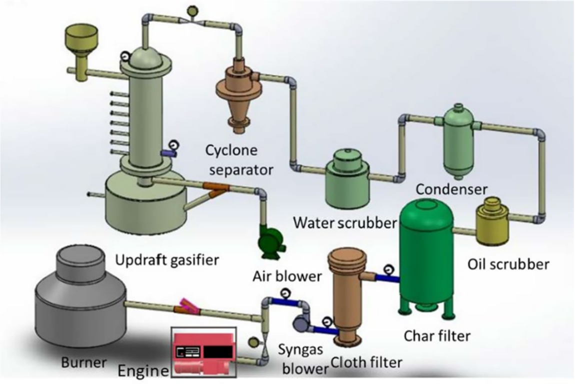


Fig. 1 The schematic diagram of the gasification system

There are significant differences between biomass and coal. Biomass is always in low energy density and presents high capacity of water absorption. Moreover, severe tar related issues are affecting the operation life of engines and incurring the channeling phenomena because the non-ideal solid–gas contacting inside the gasifier easily appears when raw biomass is directly applied in the updraft gasification process. Therefore, some pretreatments to convert biomass resources with various moisture contents and shapes into uniform fuel are essential. In this project, the biomass feedstock was initially experienced a carbonization process with less external energy consumption. Then, carbonized pellets/briquettes with high quality were produced from the crashed biomass char for the corresponding gasification. The gasifier size is as follows: inner diameter = 549.2 mm, height = 1838 mm. Carbonized pellets/briquettes were supplied from the top hopper of the gasifier. There was a sensor for determining the height of solid materials in the gasifier. Once the level of the carbonized pellets/briquettes dropped below the sensor, the screw feeder would automatically feed fuel into the gasifier. The reaction zones from the top to the bottom of the gasifier were drying, pyrolysis, reduction, and combustion. The gasifier was operated at a small negative pressure (around − 10 Pa). The detail conditions for carbonization and densification can be found in our previous study (Ding et al. 2017). Figure 1 indicates the schematic diagram of the integrated system, details are described elsewhere (Ding et al. 2018).

The gasification combined power generation process was shown in Fig. 2. Woody pellets (WP) are fed into the reactor of RP to be transferred into components shown as Eq. (1), and then mixed with air to process reactions in the GIBBS reactor where reactants reach Gibbs equilibrium. Prior to the separation process in B14, the heat in the stream PR is recycled to the power generation cycle. In B14, gas and liquid are separated and then released with streams S27 and S28, respectively. The mechanic energy in stream S27 is converted into power in turbine B13, and the outlet stream is recovered to ambient temperature with the exchanger B5. The recycled heat is used to generate power in the generation cycle, which includes the furnace, turbine, exchanger and pump.

$$\text{Woody Pellets} \rightarrow \alpha_1 H_2O + \alpha_2 O_2 + \alpha_3 N_2 + \alpha_4 C + \alpha_5 S + \alpha_6 Cl_2 + \alpha_7 H_2 + \alpha_8 ASH \tag{1}$$

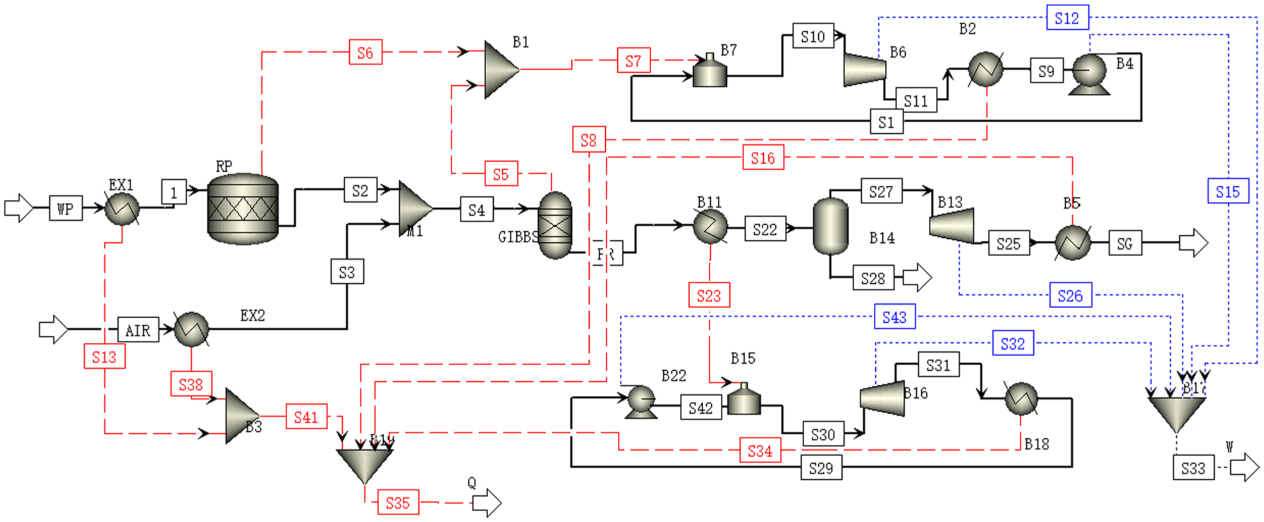


Fig. 2 Flow diagram of the gasification combined power generation process

In the Aspen plus simulation process, the woody pellets were assumed to be nonconventional components as coal. The Proximate and Ultimate analysis data was specified into Aspen component attribute setups. And this data was in turn adopted by the Fortran statements in the Aspen integrated calculator to determine the coefficients in the reaction showed in Eq. (1).

The power generation cycle in the process flow chart uses the heat from reactions and mechanic energy to generate power. The furnace accepts the heat to evaporate the water, which transfers into steam with 80 bar. The steam is fed into the turbine to generate power and subsequently is discharged at the pressure of 1.1 bar. Next, the steam is fed into the exchanger to condense into liquid water, which in turn is pressed up to 80 bar to proceed the generation cycle. Moreover, to transfer mechanic energy in syngas into power, there is a turbine which is propelled by the syngas stream S27. All the power generated is denoted by blue lines and mixed into the mixer B17.

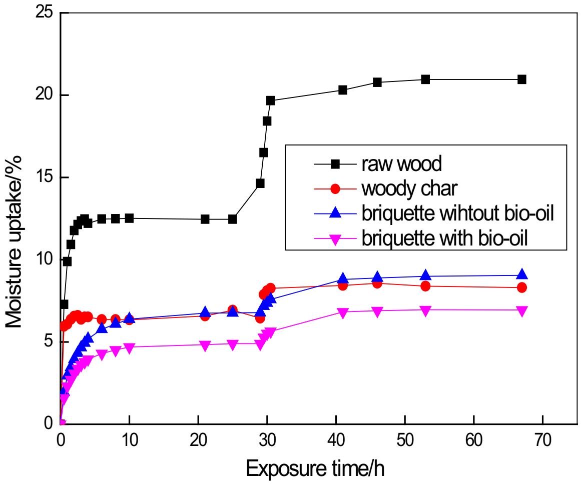


Fig. 3 Moisture uptake characteristics at 70% (0–30 h) and 90% relative humidity (30–68 h)

3 Results and discussion

3.1 Selection of the feedstock for continuous gasification process in updraft gasifier

Carbonized biomass char was firstly crushed, and then densified before being fed into the gasification system.

3.1.1 Utilization of bio-oil as an auxiliary binder for densification

There were several advantages for using bio-oil as an auxiliary binder for densification, like improving the hydrophobicity, the reactivity and the strength of pellets or briquettes. It is interesting to find that the time requirement for making high strength briquettes and the hydrophobicity of carbonized briquettes could be significantly improved by adding bio-oil as the binder. Figure 3 shows the moisture uptake characteristics of different samples, and carbonized briquettes with bio-oil addition presented the highest hydrophobicity. During our combustion test of carbonized briquettes, it was found that the dust was significant when only adding poval or corn starch as the binder, while after adding bio-oil, briquettes could keep their morphological shape during the whole combustion process, which was very important for maintaining the stable operation of the gasification system.

As mentioned above, bio-oil was an ideal binder for making high quality briquettes/pellets, and actually it could be self-supplied from the carbonization system. It is noted that the heat from the combustion of volatile matters was always excessive during the carbonization process. Therefore, the carbonizer could be modified so that a certain amount of bio-oil could be extracted out and condensed from the release volatiles (Ding et al. 2017). This modification can greatly reduce the cost of the whole briquetting/pelletization process.

3.1.2 Comparison of the gasification characteristics of three densified feedstock with different compositions

Three types of densified products, i.e., carbonized pellets, carbonized briquettes and the mixture of them (the mass ratio is 1:1) were tested, respectively to evaluate which type of densified feedstocks would be more suitable for realizing continuous and stable gasifier running as well as high efficiency of the whole gasification and power generation system. The characteristic data of carbonized briquettes/pellets and their mixture are shown in Table 1.

Figure 4 shows that CO and H_2 concentrations were kept almost constant after the system reached the stable state. It took a shorter time for carbonized pellets than carbonized briquettes to reach the stable stage. Figure 5 indicates that carbonized pellets showed the highest low heating value of the syngas during the stable stage.

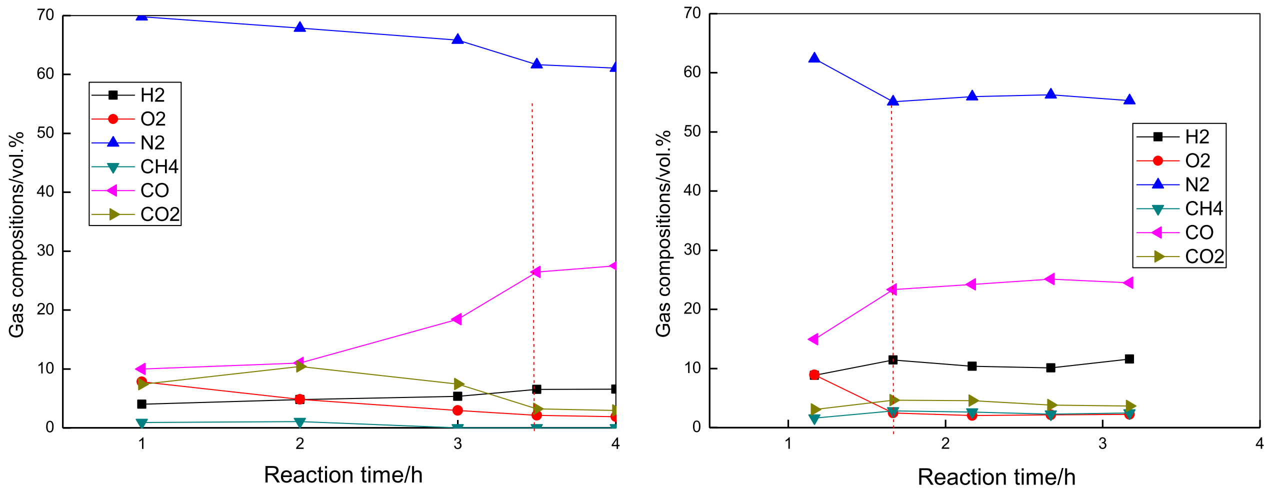
Usually, the equivalence ratio (ER) is the key operating parameter for the air gasification applications, which is shown as follows (Hu et al. 2016):

$$\mathrm{ER} = \frac{(\mathrm{Air}_{\mathrm{kg}}/\mathrm{Dry\ woody\ pellet\ or\ briquette}_{\mathrm{kg}})_{\mathrm{actual}}}{(\mathrm{Air}_{\mathrm{kg}}/\mathrm{Dry\ woody\ pellet\ or\ briquette}_{\mathrm{kg}})_{\mathrm{stoichiometric}}} \tag{2}$$

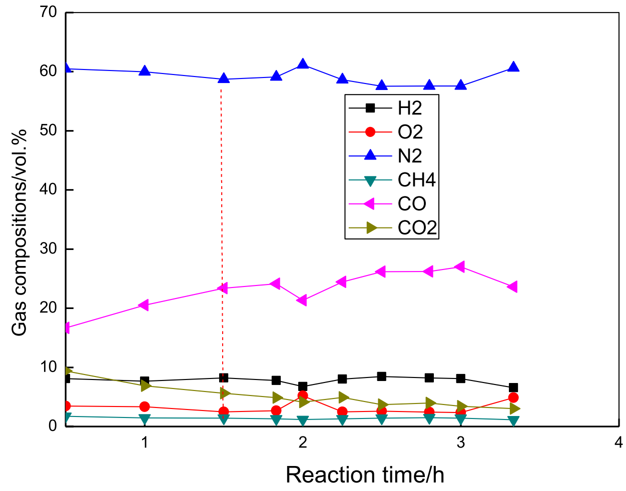
Table 1 Characteristic data of carbonized briquettes/pellets and their mixture

Sample	Proximate analysis (dry, wt%)			Ultimate analysis (dry, wt%)				LHV (MJ/kg)	Chemical formula
	VM	FC	Ash	C	H	N	O		
Carbonized briquettes	27.13	70.37	2.50	82.81	2.74	0.35	11.51	34.3	$CH_{0.397}O_{0.104}N_{0.004}$
Carbonized pellets	36.76	61.93	1.31	79.05	3.70	0.27	16.59	32.7	$CH_{0.437}O_{0.157}N_{0.003}$
Mixture of Carbonized briquettes and pellets	33.65	64.54	1.80	80.36	3.17	0.32	14.82	31.9	$CH_{0.473}O_{0.138}N_{0.003}$

VM, volatile matter; FC, fixed carbon; d, dry basis; LHV, denotes the low heating value of samples



(a) Carbonized briquettes (b) Carbonized pellets

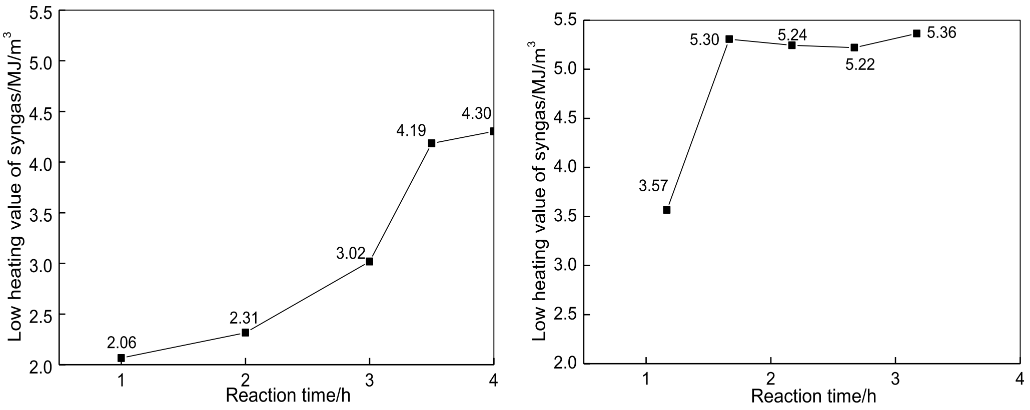


(c) Mixture of Carbonized pellets/briquettes

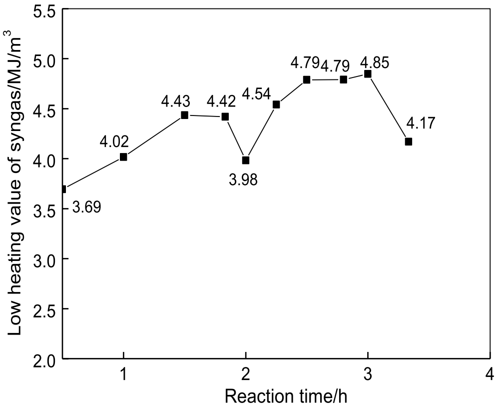
Fig. 4 Variation of syngas compositions with time. **a** Carbonized briquettes; **b** Carbonized pellets; **c** Mixture of carbonized pellets/briquettes

The cold gas efficiency (CGE) and the carbon conversion efficiency (CCE) during the stable stage were evaluated according to the following equations (Hu et al. 2016):

$$\mathrm{CGE} = \frac{LHV_{\mathrm{gas}} \times Q_{\mathrm{gas}}}{LHV_{\mathrm{fuel}} \times Q_{\mathrm{fuel}}} \times 100\% \quad (3)$$



(a) Carbonized briquettes (b) Carbonized pellets



(c) Mixture of Carbonized pellets/briquettes

Fig. 5 Variation of low heating value of syngas with time. **a** Carbonized briquettes; **b** Carbonized pellets; **c** Mixture of carbonized pellets/briquettes

$$\mathrm{CCE} = \frac{C_{\mathrm{gas}}}{C_{\mathrm{fuel}}} \times 100\% \tag{4}$$

Note: LHV_{gas}—The average low heating value of syngas, (MJ/Nm^3); Q_{gas}—The average flow rate of syngas, (Nm^3/h); LHV_{fuel}—The average low heating value of solid fuel, (MJ/kg); Q_{fuel}—The average feed rate of solid fuel, (kg/h); C_{gas}—Total carbon amount in the syngas, (kg); C_{fuel}—Total carbon amount in solid fuel, (kg).

Table 2 indicates that the cold gas efficiency (CGE) shows a positive correlation with the carbon conversion efficiency (CCE). Carbonized pellets showed higher CCE and CGE when compared to carbonized briquettes or the mixture of these two solid fuels due to the high reactivity of carbonized pellets. Carbonized briquettes took the spheroid shape (equatorial radius = equatorial radius = 1.5 cm and polar radius = 1.0 cm), while carbonized pellets took the cylindrical shape with radius = 4 mm, length = 0.5–2.0 cm. As the particle size of carbonized pellets was much smaller than that of carbonized briquettes used in the present study, the reaction surfaces of pellets were much larger than that of briquettes. Moreover, the dehydration of newly produced

Table 2 Variations of ER, CCE and CGE with different solid fuels

Performance parameters	Carbonized briquettes	Carbonized pellets	Mixture of carbonized pellets/briquettes
Carbon conversion efficiency during stable stage	45.1%	57.8%	55.3%
Cold gas efficiency during stable stage	37.1%	45.6%	41.9%
ER during stable stage	0.24	0.24	0.26

ER shows a bit difference for the case of mixture of carbonized pellets/briquettes, due to slight fluctuation of air flow rate during the continuous operation of the gasification system carbonized pellets after densification were much easier than that of newly produced carbonized briquettes under natural drying conditions due to the smaller particle size. For the production of syngas with a reasonably high heating value, most gasification systems use dry biomass with the moisture content of 10 wt% – 20 wt% (Basu 2013). In this study, the moisture content of carbonized pellets was below 10 wt%. Considering all the results mentioned above, carbonized pellets were chosen as the main feedstock for the 100 h open-field test.

3.2 100 h continuous gasification test of carbonized pellets in the open-field

3.2.1 The temperature distribution and pressure loss analysis

Figure 6 shows the time change of the temperature distribution in the gasifier during the 100 h continuous operation, which demonstrates that the system was kept stable during most of the operation time. But the syngas blower stopped twice during the operation time of 70–80 h due to the tar blocking issue. The system could be started again after the condensed tar depositing in the syngas blower was cleaned. Although carbonized pellets were adopted for reducing tar production as much as possible, more attentions should still be paid for syngas purification during long time continuous operation. We can fix this issue by preparing an alternative blower during the future application. Also, the bypass pipe lines can be prepared from the outlet of the cyclone separator to the inlet of the water scrubber to avoid too much tar components mixed with dust depositing within this pipe section. Figure 8 shows that the pressure loss in each facility increased sharply after running 60 h, which was mainly caused by tar condensation. Therefore, providing bypass lines to clean the devices and pipes with tar accumulation regularly are necessary for long time operation in the future.

Based on the pressure loss data of each facility in Fig. 7, the pressure loss will keep stable and lower than 3 kPa within 30 h continuous operation. Therefore, we could switch to the bypass pipe lines each 30 h, and several physical and chemical cleaning methods could be considered for the purification of the pipes lines with condensed tar including high temperature steam purging or organic (Poly vinyl alcohol) dissolution.

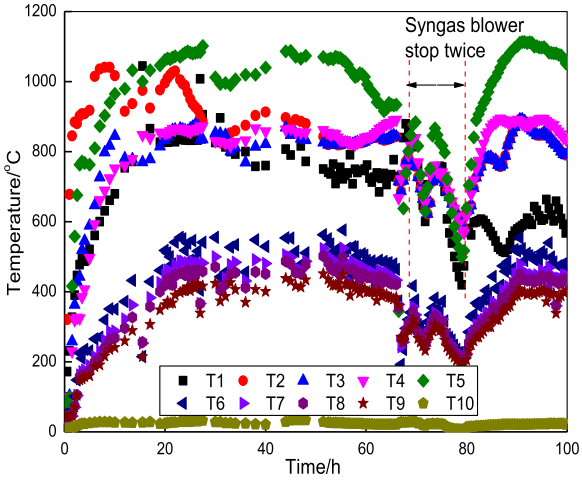


Fig. 6 Time change of the temperature distribution in the gasifier. **a** Mass balance, **b** Energy balance

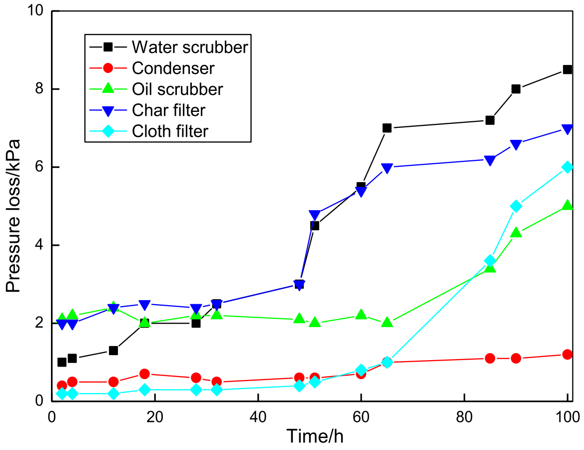


Fig. 7 Time change of the pressure loss in each facility

3.2.2 Material balance and energy balance analyses

Table 3 shows that the carbon balance was well realized during 100 h operation. The mass balance and energy balance of carbonized wood pellets during the stable stage in the pilot-scale gasification test are shown in Fig. 8. The system efficiency for power generation can be calculated as follows:

$$\eta_s = \frac{\text{Output Power}}{LHV_{\text{wood}} \times Q_{\text{wood}}} \times 100\% \tag{5}$$

Table 3 Summary of gasification data of carbonized pellets

Material	Parameter
Inlet air	3942.0 kg
Inlet pellets	1275.4 kg
Water content in pellets	4.0 wt%
Outlet syngas	4909.7 kg
Total residue	315.5 kg
Total carbon in pellets	914.2 kg
Total carbon in residue	269.9 kg
Total carbon in syngas	663.6 kg

(a) Mass balance

(b) Energy balance

Fig. 8 Mass balance and energy balance of carbonized wood pellets during stable stage

The system efficiency combining carbonization, pelletization, updraft fixed bed gasification, and power generation was 9.5% for waste wood block adopted in our project, and the corresponding value combining downdraft fixed bed gasification and power generation of raw wood waste in Chaves's (Chaves et al. 2016) and Boloy's work (Boloy et al. 2011) were both around 10%. The main advantage of our system is that the biomass pretreatment including carbonization and pelletization will reduce tar generation and meanwhile keep the whole system more stable due to uniform shape and high strength of carbonized pellets. Moreover, the outlet temperature of the exhaust gas from the updraft fixed bed gasifier (around 100 °C) was much lower than that from downdraft fixed bed gasifiers (200–300 °C), which was favorable for arranging smaller size facilities for gas cooling, and this is very important to miniaturize the whole system.

3.2.3 Syngas quality and tar removal efficiency analysis

Figure 9 shows that the low heating valve of syngas was over 4 MJ/m^3 when the system could be kept stable. A certain amount of air may leak into the system due to the negative pressure operation. During the stable operation within 50 h, the tar content after the purification was below 1 g/m^3 as shown in Fig. 10. Although the tar content in syngas was not so high, the long-time accumulation of tar in the purification facilities still caused big problems for the system stability which was stated above.

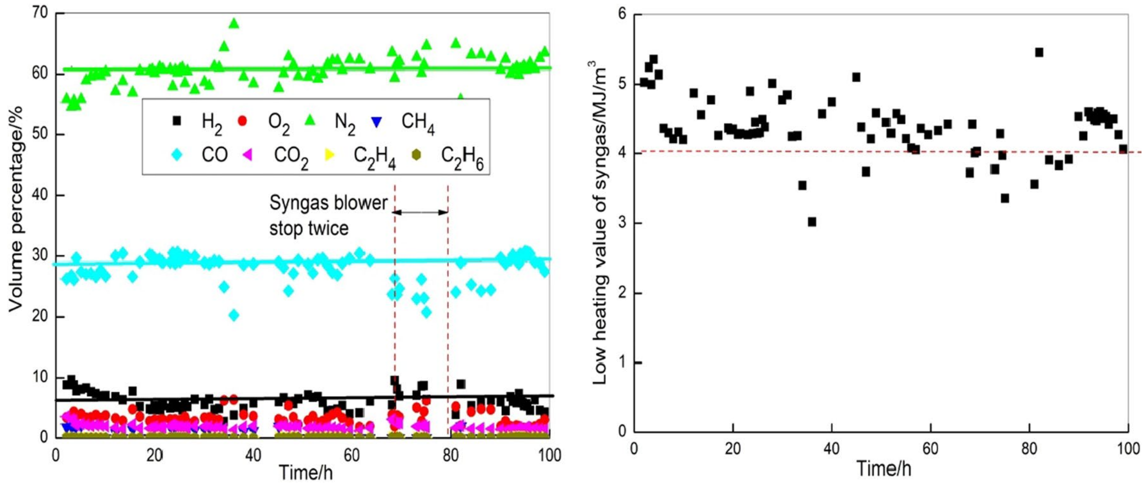


Fig. 9 Time change of compositions and low heating value of syngas

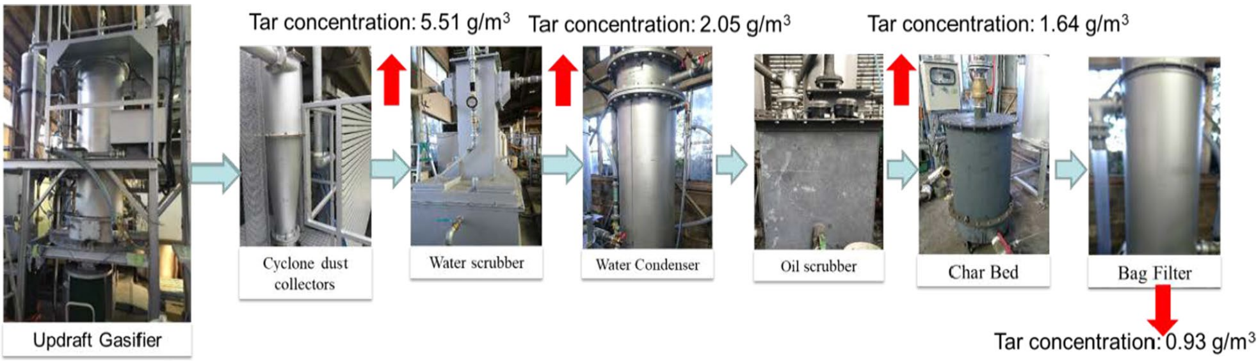


Fig. 10 Tar removal performance during the gasification process of carbonized pellets

Table 4 The carbon conversion efficiency and cold gas efficiency of carbonized pellets

Item	Value
Carbon conversion efficiency	70.5%
Cold gas efficiency	49.2%
ER	0.32

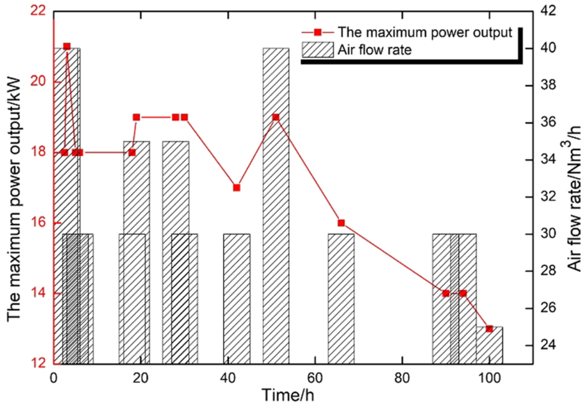


Fig. 11 Time change of the maximum power output

3.2.4 Power generation process analysis and simulation

Table 4 shows the carbon conversion efficiency and cold gas efficiency of carbonized pellets during 100 h tests. The overall efficiency of the gas engine during the stable operation stage was evaluated according to the following equations:

$$\mathrm{SGC} = \frac{Q_{\mathrm{gas}}}{(V_{\mathrm{out}}) \times I} \tag{6}$$

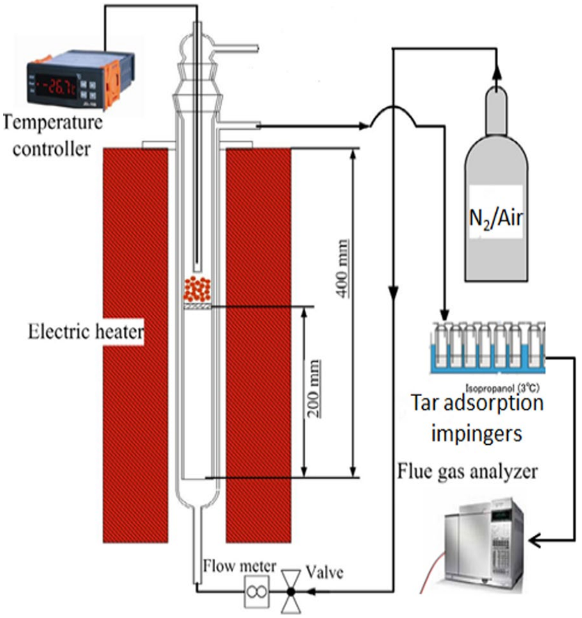


Fig. 12 Fixed bed gasification system

$$\eta_{\mathrm{E}} = \left(\frac{3600}{1000 \times (LHV_{\mathrm{G}}) \times \mathrm{SGC}} \right) \times 100\% \tag{7}$$

Note: V_{out}-output voltage of electric generator (V); I-output current of electric generator (A). Q_{gas}-gaseous average flow rate (Nm^3/h); LHV_{G}-heating value of the producer gas (MJ/Nm^3); SGC-specific gas consumption (Nm^3/kW h); η_{E} -Overall efficiency of engine.

After calculation, the average low heating value of the syngas during stable power generation stage was 5.11 MJ/m^3, and the maximum output power was 21 kW at the air flow rate of 40 Nm^3/h during the gasification of carbonized pellets, and the corresponding overall efficiency of the gas engine by using the syngas was about 20.3%.

Figure 11 shows the time change of the power output during the 100 h operation. Due to the noise problem of the engine, it was operated during the day time only. Although the power output was still around 15 kW even at the late running stage, the high pressure loss of the whole system limited the power output capacity. Therefore, the syngas purification system shall be further optimized so that the pressure loss can be maintained as low as possible during the future application. Anyway, this technology will be feasible once the bypass lines are considered carefully to be able to conduct the maintenance work without stopping the facility.

Although by adding bio-oil, the pellet quality could be improved a lot, the tar amount might sharply increase, which caused the continuous operation of the power generation system. The gasification tests of wood pellets with/without bio-oil as binder were carried out in a lab-scale fixed bed gasifier to clarify tar generation. The facility diagram is shown in Fig. 12, and the detail descriptions can refer to our previous publication (Ma et al. 2016). As shown in Fig. 13, it is indicated that the tar amount in syngas was around 1 mg/Nm^3 at 800 ℃ for the woody char, while after adding bio-oil as the binders, the tar generation during carbonized pellets gasification significantly increased to around 3 mg/Nm^3. Therefore, bio-oil should be avoided as the binder for the densification process of waste wood char for a steady operation of the gasification process. Related contents have been added in our revised manuscript.

As shown in Table 5, the total electricity consumption of the main facilities during gasification was 7.55 kW. The gasification system can be operated by using a part of the electric power generated from the engine and this can be applicable to open-field without power supply. Actually, due to the limit of the total amount of the feedstock prepared, we could only conduct the test with a low air flow rate (40 m^3/h). If the air flow rate could be increased to high enough values, the maximum power output of 30 kW of the syngas engine would certainly be realized.

Table 5 Electricity consumption of the main facilities during gasification

Facility	Maximum electricity consumption (kW)
The gasifier related device	0.80
The air blower	3.30
The syngas blower	2.20
Cyclon separator	0.20
Water scrubber	0.25
Oil scrubber	0.75
Burner	0.05
Total consumption	7.55

Process simulation of the gasification process has been validated by literatures, and the absolute deviation from experimental data, for example, ranged within 4% (Singh and Tirkey 2021). In this study, woody pellets with the flow rate of 20 kg/h could generate a 15.18 kW power at the air flow rate of 40 Nm^3/h, which is in a good agreement with experimental study of 15 kW in the 100 h operation. It is indicated that the gasification combined power generation cycle simulated by Aspen simulator could achieve reliable data to assist the complicated experimental operation.

In the GIBBS reactor, pyrolysis products react with oxygen entrained within the stream AIR, and minimizing the Gibbs free energy, and then the system reach reaction equilibrium. Figure 14 shows the influence of air flow rate on the component flow rate in syngas stream SG. Due to the oxidation by oxygen, the hydrogen flow rate decrease as more air is introduced into the system, which is converse to that of

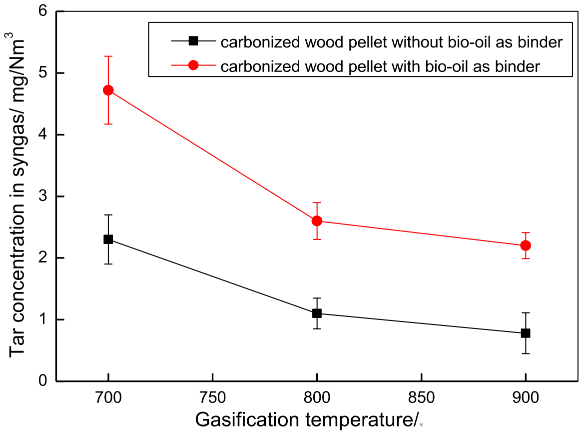


Fig. 13 Tar concentrations of carbonized wood with/without bio-oil as binder during gasification

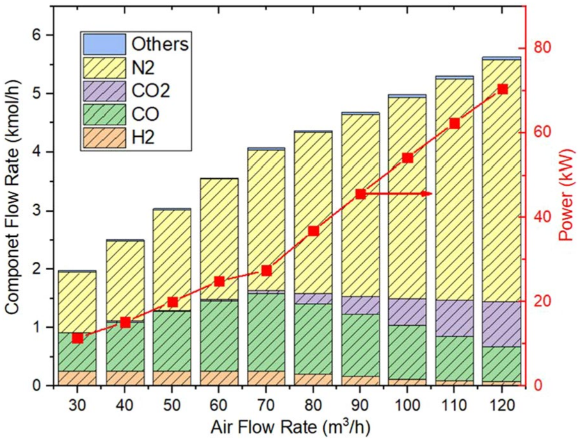


Fig. 14 Variation of component flow rate and power influenced by air introduced

the CO_2 component in SG because it is an oxidation product. The CO component acts as the product, and becomes the reactant as the air flow rate increases, so the component flow rate of CO has a maximum value with the increase of air flow rate. It is no doubt that N_2 increases with the increase of air flow rate because it is an inert component in this system.

The power generated is affected by the extent of gasification that can reach up. When the air introduced increases, more C and CO will be consumed and more heat will be released from the oxidation. As shown in Fig. 14, increasing the flow rate of air inlet, the total power generated increases. Determined by the residue amount of C, the generated syngas and power are two related factors. While there is some C residue existed, and the more air fed, the more both effective components in syngas ($CO+H_2$) and power generated. As the flow rate of air surpass 70 m^3/h, the power generation could be supported by more heat provided from the oxidation of CO and H_2, and the effective components in syngas ($CO+H_2$), however, decrease. With those features, users could adapt the amount of air employed to change the power and syngas loads, based on their requirements.

4 Conclusions

A distributed power generation system based on carbonized wood pellets gasification was proposed in this study. The tar content in the syngas from the outlet of the updraft fixed bed gasifier decreased significantly when carbonized pellet/briquette were used. Moreover, the tar removal efficiency can be further improved by coupling with several secondary purification devices including a water scrubber, an oil scrubber, a char filter and cloth filter. The 100 h continuous operation indicates that the comprehensive process covering carbonization, densification, gasification, syngas purification and engine system is feasible for small-scale power generation with a well-designed system providing bypass lines to clean the devices and pipes with tar accumulation every 30 h. Besides, bio-oil will not be included as a binder for the densification of carbonized biomass as we optimized the pelletization conditions with the natural binder in biomass itself. The results from the simulation of gasification combined generation cycle indicated that syngas and power could be simultaneously produced with carbonized woody as feedstock, and there is a good operating flexibility to calibrate the power or syngas production, which facilitated the user requirements.

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Author contributions All authors read and approved the final manuscript.

Declarations

Competing interests All data in this work would be provided as required. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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