SYNTHESIS OF SYNGAS FROM MUNICIPAL SOLID WASTE IN A FLUIDIZED BED GASIFIER

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In this study, three representative materials, wood, paper, and cloth from municipal solid waste, were studied separately in an atmospheric fluidized bed gasifier. The effects of different feedstock, equivalence ratio, gasification temperature, and calcium carbonate presence on syngas composition, the lower heating value, and carbon conversion efficiency were investigated at different operating temperatures (800-950°C), and the equivalence ratio range from 0.2 and 0.5. As the equivalence ratio increased, the yields of syngas and its lower heating value decreased, whereas the CO_2 yield and carbon conversion efficiency increased generally from wood gasification. Higher gasification temperature favored enhancing the CO and H_2 yield and lowering the CO_2 yield while the lower heating value and carbon conversion efficiency of syngas increased. Different variations of CO_2 yield and the lower heating value of syngas were observed in different feedstock gasification. $CaCO_3$ was more supportive for enhancing the yields of syngas components (H_2, CO, and CH_4) and lowering the CO_2 yield, while a lower heating value of syngas was also increased from different feedstock gasification. However, an optimum temperature of 900°C was the highest lower heating value of syngas, reaching 8000 kJ/Nm^3 from wood gasification.

Key words*: Municipal solid waste; fluidized-bed; syngas; gasification; $CaCO_3$*

1. Introduction

Nowadays, the generation of municipal solid waste (MSW) has rapidly increased; therefore, its proper treatment, management, and disposal have become critical challenges in every developing country [1, 2]. It is expected that the production amount of MSW will reach 2025 around 1.42 kg/capita/day [3], and it will probably hit 2.6 billion metric tonnes by the year 2030 [4, 5]. MSW is known as a valuable fuel for energy sources [6]. It is a complicated diverse resource that contains a high fraction of organic compounds such as wood, food waste, papers, plastics, cotton, and leather [7]. The average fraction of combustible solid wastes is approximately 81% in MSW [8]. The landfilling and incineration are common disposal methods for MSW used globally [9]. Over the past few decades, the landfilling method has also encountered some issues related to land shortage, human health, leachate

disposal, and the environment, such as water and air pollution [10]. Incineration technology has played a vital role in the field of waste management due to its benefits, which results in substantial reductions in waste volume, energy recovery, and complete disinfection [11]. However, it has problems limiting polychlorinated dibenzofurans (PCFS/DD) and polychlorinated dibenzo-p-dioxins emissions along with final disposal of burnt ash, heavy metals, particulate matter, as well as its efficiency when utilizing energy, is low [5].

MSW pyrolysis and gasification are promising thermochemical treatment methods [12]. Both techniques can significantly reduce the waste volume over traditional incineration and are regarded as highly efficient as well as legal techniques for recycling MSW [13]. Pyrolysis always occurs in an anaerobic atmosphere, which produces char, liquid, and gas end products. Meanwhile, the gasification technique converts carbonaceous matter (e.g., biomass, coal, and other waste streams) through partial oxidation into synthesis gas [14]. Among these, the gasification technique is getting increasing attention. It is becoming one of the best directions of the current continuous development research [15] and alternatives for the recycling MSW due to its capability to reduce the emission of dioxins heavy metals as well as generate a higher quantity of cleaner gaseous fuel such as syngas and hydrogen than combustion and pyrolysis [16]. Many researchers investigated the potential of MSW gasification processes by using different feedstock characteristics, reactor configurations (such as fluidized beds, plasma furnaces, and others [17], gasifying medium (air, oxygen, and steam), and addition of catalyst (such as dolomite, nickel, and calcium-based compounds [18] for the production of synthesis gas. However, studies on the impact of added $CaCO_3$ on the syngas yield generated from different materials are rare.

The target of this research is to investigate the effect of equivalence ratio (ER), gasification temperature, and $CaCO_3$ on the syngas composition, lower heating value (LHV), and carbon conversion efficiency of paper, wood, and cloth was separately studied using a laboratory-scale fluidized bed gasifier (FBG). This data would support gasifier operation and design and assist the scientific knowledge to expedite the practical use of the gasification technique.

2. Experimental

2.1. Materials

In this study, three materials (paper, cloth, and wood) were used. Before experiments, the materials were dried in an oven at 105 °C for 24 hrs to eliminate the moisture content. Finally, the dried pulverized material was sieved through 0.10 mm mesh. The $CaCO_3$ was used as the catalyst at 5% (w/w) of the feedstock. The feedstocks (paper, cloth, and wood) were collected from Zhenjiang, Jiangsu, China. Their properties on an air-dried basis are summarized in tab.1.

Table 1. Properties of materials.

Proximate analysis	Paper[a]	Wood[a]	Cloth[a]
Moisture	3.04	4.12	1.09
Volatile matter	75.96	76.75	81.67
Fixed carbon[b]	10.67	14.76	15.68

Ash	10.35	4.36	1.56
Ultimate analysis			
Carbon	33.57	43.97	58.8
Hydrogen	4.18	5.32	4.85
Oxygen[b]	40.47	43.97	25.4
Nitrogen	0.14	0.12	5.14
Sulfur	0.06	0.04	0.16
LHV (MJ/Kg)	10.73	17.82	16.13

[a] Air-dried basis (wt%).

[b] By the difference.

2.2. Facilities and procedures

The experimental work was carried out in an FBG with air as a gasification agent and $CaCO_3$ as a catalyst, respectively. A schematic diagram of the experimental setup is depicted in fig. 1.

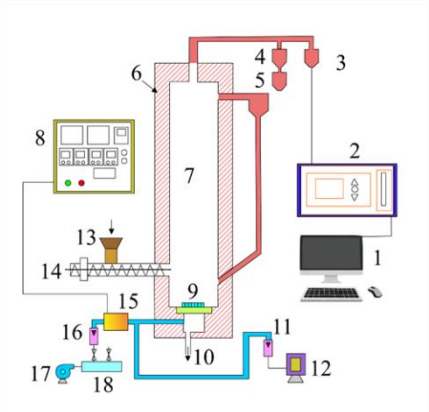

Figure 1. Experimental setup of FBG facility.

1- Data acquisition system 2- Gas analyzer 3- Cyclone (2) 4- Cyclone (1) 5- Ash collector 6- Insulation layer 7- Gasifier 8- Temperature controller 9- Air distribution plate 10- Slag discharge tube 11- Rotor flow meter 12- Steam generator 13- Hopper 14- Screw feeder 15- Air preheater 16- Rotor flow meter 17- Blower 18- filter

The FBG has a maximum processing capacity of 20 kg/h with a total height of 4 m and an internal diameter of 0.108 m. The maximum thermal efficiency of the gasifier was about 60 kW. The air was fed to the bed through the sieve grate. In these experiments, bauxite was used as a bed material with a particle size mesh of 60 – 80 mm. To start with each experiment, 2 kg of bed material was fed to the reactor using the spiral feeder. The fuel flow in the gasifier will be stopped once the FBG temperature reaches a steady level. After that, the feedstock was introduced to the reactor through the spiral feeder, and finally, the gasification started. The gaseous products were collected in the gas bag. Non-condensable gases collected in the gasbags were analyzed with the gas board-3100 line. An infrared flue gas analyzer was used for recording gas data.

The FBG was fed with the three different materials by keeping the size range and fixed the type of the bed material, the fluidized bed velocity of 0.4 m/s, and the fluidized flow of 5 m^3/h, the gasifying agent (air) to get the information about the characteristics of feedstock with catalyst and without catalyst, temperature, and ER on the composition and LHV of syngas along with carbon conversion efficiency. The experimental runs are shown in tab. 2.

Table 2. Gasification experimental runs.

Feedstocks	Catalyst(%)	Temperature (℃)	ER
Wood	0	800 - 950	0.2
Wood	0	850	0.2 - 0.5
Wood	0	850	0.2
Paper	0	850	0.2
Cloth	0	850	0.2
Wood	5	900	0.2
Paper	5	900	0.2
Cloth	5	900	0.2

3. Results And Discussion

The main relevant reactions involved in this gasification [19] can be listed in tab. 3.

Table 3. Relevant gasification reactions.

Reactions		
Oxidation		
$C + O_2 \rightarrow CO_2$	-393 kJ/mol	(1)
$C + 1/2O_2 \rightarrow CO$	-110 kJ/mol	(2)
Carbon reaction with carbon dioxide		
$C + CO_2 \rightarrow 2CO$	+172 kJ/mol	(3)
Carbon reaction with steam		
$C + H_2O \rightarrow CO + H_2$	+131.5 kJ/mol	(4)
Methanation reaction		
$C + 2H_2 \rightarrow CH_4$	-74.8 kJ/mol	(5)
Water-gas shift		
$CO + H_2O \rightarrow CO_2 + H_2$	-41 kJ/mol	(6)
Methane reforming reaction with Steam		
$CH_4 + H_2O \rightarrow CO + 3H_2$	+206 kJ/mol	(7)

The carbon conversion efficiency (%) was calculated as follows in eq. (8).

$$X_c(\%)=(12Y(CO\%+CO_2\%+CH_4\%))/(22.4\times C\%)\times 100 \quad (8)$$

Here, Y is the yield of gas in Nm^3/kg, C% is the mass of carbon in percentage from the ultimate analysis of the feedstock, while others are the molar fractions of components in the syngas of MSW.

3.1. Effect of Temperature

Fig. 2 (a,b) displays the effect of temperatures ranging from 800 to 950°C at constant ER 0.2 on carbon conversion efficiency, LHV, and syngas composition from wood gasification is being discussed.

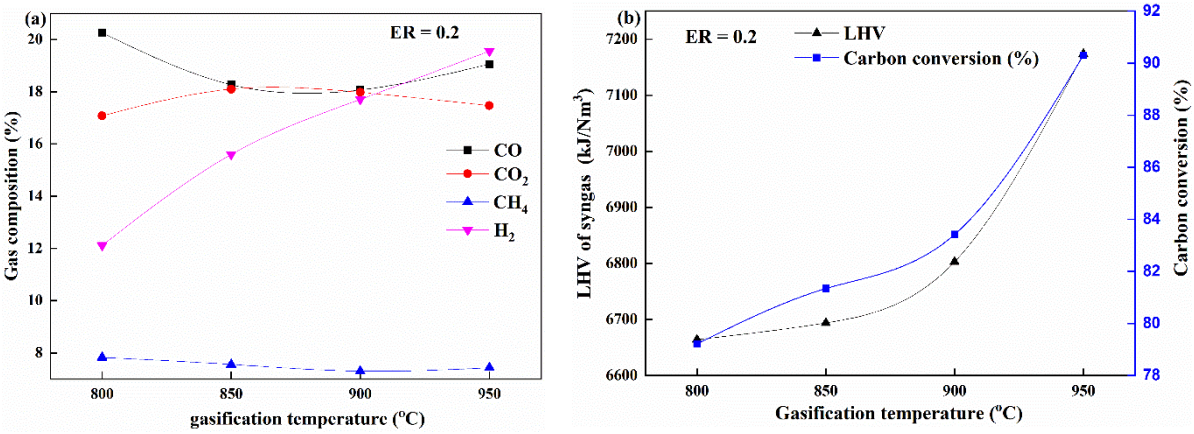

Figure 2. Effect of gasification temperature on (a) syngas composition, (b) LHV of syngas, and carbon conversion efficiency.

The composition of the syngas was significantly influenced by gasification temperature. Since, due to an endothermic reaction, the end product of gas composition responds to changes in temperature. It was noticed in fig. 2(a) that with the increase in temperature, syngas composition varies significantly. As the gasification temperature increases from 800–950°C, the H_2 yield significantly rises from 12 to 20% (by vol.). This can be explained by the gasification reaction's endothermic nature, which is stated in tab. 3. Gasification temperatures ranged from 800 to 950°C, and synthetic gas composition and the H_2 yield were mainly due to the water–gas shift reaction [20]. According to the water gas reaction, both CO and H_2 were produced more frequently at higher gasification temperatures, so the conversion of CO and H_2O into CO_2 and H_2 is enhanced at higher temperatures. The CO_2 yield decreased as the gasification temperature increased. This is because endothermic reaction predominated more, moving the reaction towards the right and causing a rise in CO yield and a decrease in the CO_2 yield as the gasification temperature increased. The same trend in literature has been noticed [21]. On the other hand, higher temperatures resulted in a lower CH_4 volume fraction in the product gas. The decrease in CH_4 yield is due to the methane reforming reaction with steam, which then raises the H_2 and CO yield in synthetic gas.

The LHV of syngas from MSW generally depends on the H_2, CO, and CH_4 yields were calculated as follows in eq. (9) [3].

$$LHV_{syngas}\ (kJ/Nm^3) = (30CO + 25.7H_2 + 85.4CH_4) \times 0.0042 \quad (9)$$

Here, the CH_4, CO, and H_2 are the molar fractions of components in the syngas of MSW.

Fig. 2(b) depicts the LHV of syngas and carbon conversion efficiency as a function of gasification temperature ranging from 800–950℃ at constant ER 0.2. LHV of syngas reached about 6600–7100 kJ/Nm^3. It shows that higher temperature accelerated in higher LHV. As was observed in fig. 2(b), increasing the gasification temperature also responds to an increase in the carbon conversion efficiency. This tendency can be explained by how the increased gasification temperature would shift the direction of the endothermic reactions (3), (4), and (7) to the right, increasing the efficiency of carbon conversion [22]. Under experiment conditions, the optimum wood gasification conditions were identified as a temperature of 950℃ with ER 0.2 LHV of syngas reaching about 7100 kJ/Nm^3, and the carbon conversion efficiency was achieved at about 90%.

3.2. Effect of the ER

Fig. 3(a,b) indicates the effect of ER range of 0.2 to 0.5 at the gasifier temperature of 850℃ on carbon conversion efficiency, LHV, and syngas composition from wood gasification is discussed.

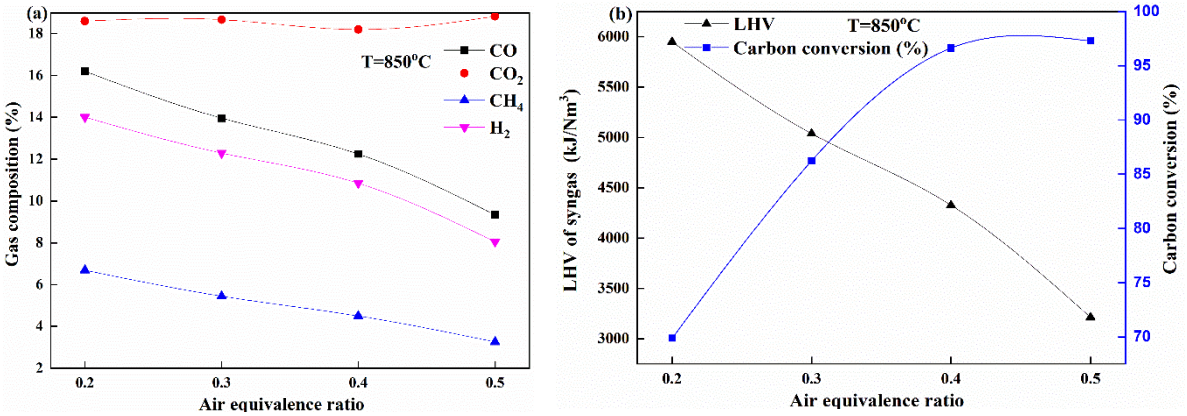

Figure 3. Effects of ER on (a) syngas composition, (b) LHV of syngas, and carbon conversion efficiency.

The ER is the most significant operating factor and has a strong influence on carbon conversion efficiency, LHV, and syngas composition. The yield of CO_2 rises linearly with ER while the LHV and combustible gas component of syngas decline. Higher ER promotes oxidation reactions and lowers the value of syngas [21]. Both H_2 and CO yields significantly deteriorate as ER increases. The enhanced oxidation reactions could address the increase of CO_2 yield with ER. Meanwhile, the CH_4 yield remains lower and slightly decreases throughout the experiment's conditions.

The LHV decreased significantly as the ER increased, which can be explained by reactions (1) and (2). The LHV was declined due to the decrease of combustible gas components. The LHV of syngas significantly dropped from 5950 kJ/Nm^3 to 3200 kJ/Nm^3, as observed in fig. 3(b). The maximum value of LHV could be up to 5950 kJ/Nm^3 when ER is 0.2. The carbon conversion efficiency increased linearly and reached a maximum value as the ER increased, as shown in fig. 3(b). This can be explained by the oxidation reactions (1), (2) and (3). The maximal wood gasification conditions were identified as a temperature of 850℃ and an ER of 0.2. In these circumstances, the LHV of syngas reached about 5950 kJ/Nm^3, and the carbon conversion was achieved by about 70%.

3.3. Effect of Feedstock

The effect of cloth, paper, and wood on carbon conversion efficiency, LHV, and syngas composition at the temperature of 850°C and the ER of 0.2 were presented in Fig. 4(a, b).

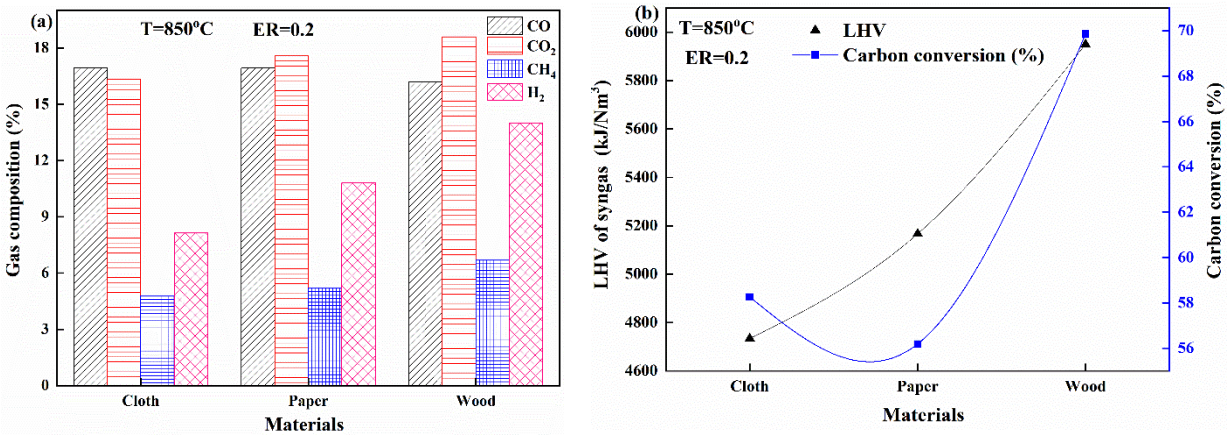

Figure 4. Effect of material on (a) syngas composition, (b) LHV of syngas, and carbon conversion efficiency.

The reaction behavior was quite different for each of the feedstock. Wood material released more syngas composition because of the high heating value of wood as compared to paper and cloth. For instance, there is a small decrease in LHV with the lower CH_4 yields for paper and cloth as compared with wood.

In wood gasification, CH_4, H_2, and CO_2 content were much higher, and CO content was lower than in paper and cloth. In the fluidized bed reactor, when temperature increased, the LHV of syngas also increased because of more syngas composition in wood gasification, as shown in fig. 4(b). For wood gasification, the heating value fluctuates more than that for paper and cloth gasification. The yield of CH_4 and H_2 were higher than paper and cloth feedstock, which is why the LHV of wood achieved at 850°C is 5950 kJ/Nm^3 at the equivalence ratio of 0.2. Therefore, the carbon conversion efficiency of wood is much higher and reached about 70% more than that of paper and cloth gasification.

3.4. Effect of $CaCO_3$ catalyst

Normally, the catalyst is used to speed up a reaction. It provides an alternative pathway that has a lower activation energy. $CaCO_3$ was chosen as a catalyst in this study for the gasification of cloth, paper, and wood because it is safe to handle, inexpensive, and has a good catalytic effect. Catalysts can also increase conversion efficiency and reduce tar formation [23]. In this experiment, we added 5% of $CaCO_3$ catalyst to investigate the influence on LHV and syngas composition at the temperature of 900°C and the ER of 0.2, which is presented in fig. 5(a, b).

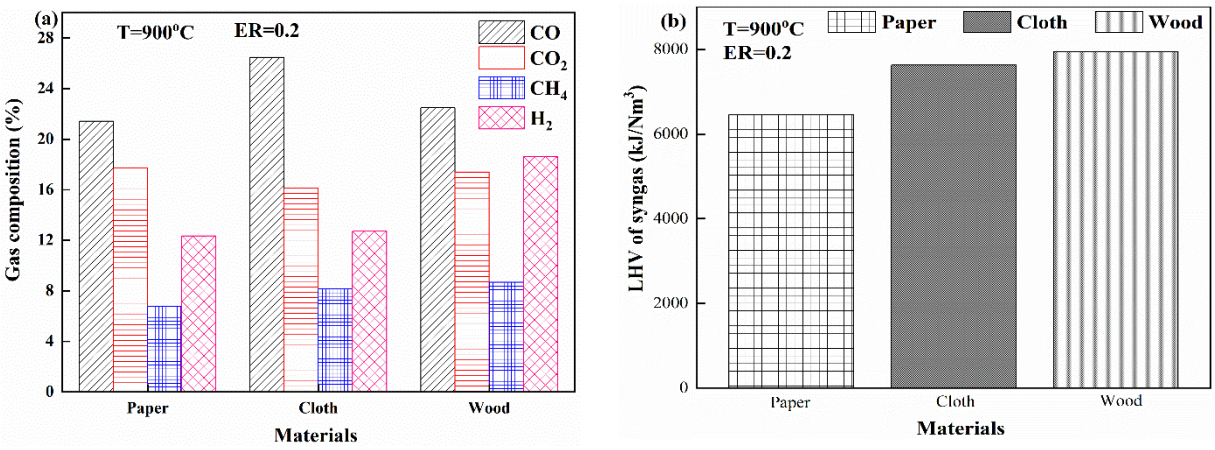

Figure 5. Effects of 5% $CaCO_3$ on (a) syngas composition, (b) LHV of syngas.

The effect of $CaCO_3$ as a catalyst on pyrolysis depends on the MSW characteristics [24]. Experimentally, it was found that the addition of 5% $CaCO_3$ significantly inhibited the generation of CO and CH_4 contents and promoted both CO_2 and H_2 yields. However, cloth with the presence of 5% $CaCO_3$ produced high CO content along with a lower CO_2 yield than wood and paper feedstock. The yield of CO_2 declines when $CaCO_3$ is used. This reduction is also proved [19], as they used CaO as a catalyst during biomass gasification, and they were capable of reducing the CO_2 yield by 25%. Through CaO carbonation, CO_2 was absorbed [19]; therefore, the yield declined, which could support the secondary tar cracking reaction, water–gas shift reaction, and reforming reactions, all of which would increase H_2 and CO yield [20]. Due to the higher moisture content of 4.12% in wood, it was clear that the composition of the syngas was more significantly affected by the presence of $CaCO_3$ during wood gasification than from paper and cloth gasification. Both the CH_4 and H_2 yields were more than cloth and paper gasification. Therefore, the LHV of wood was higher than cloth and paper gasification and reached an optimum of about 8000 kJ/Nm^3.

4. Conclusion

In this study, the effect of ER ranges from 0.2 to 0.5, gasification temperature ranges from 800 to 950°C, and the presence of $CaCO_3$ as a catalyst on carbon conversion efficiency, LHV, and syngas composition of paper, wood, and cloth was performed using a laboratory-scale FBG. The results obtained in this work show that the effect of gasification temperature on carbon conversion efficiency, LHV, and syngas composition from paper, wood, and cloth gasification were different. Higher gasification temperature was more promotive to enhancing both H_2 and CO yields while declining CO_2 yield. For wood, there was a suitable temperature of 950°C and ER of 0.2 for the optimum syngas quality, and LHV at its maximum of 7100 kJ/$Nm^{3,}$ and the carbon conversion efficiency was achieved about 90% than paper and cloth gasification. As the ER increased, the LHV of syngas and combustible gas components decreased, whereas the CO_2 yield and carbon conversion efficiency increased for wood as compared to paper and cloth gasification. For wood, the optimum temperature of 850°C and the ER of 0.2 for the highest LHV of syngas reached about 5950 kJ/Nm^3, and the carbon conversion efficiency was achieved by about 70%. Various levels of gasification performance during paper, wood, and cloth gasification were observed using $CaCO_3$ as a catalyst. Due to CaO carbonation, CO_2 was absorbed, and

the explosive gas components increased from the gasification of different feedstock under the air atmosphere, which led to a decrease in the CO_2 yield. The presence of 5% $CaCO_3$ with wood feedstock at the temperature of 900℃ and ER of 0.2 facilitated the generation of syngas composition. Due to this, the LHV of wood with the presence of 5% $CaCO_3$ reached the optimum of about 8000 kJ/Nm^3, which is higher than cloth and paper gasification. This fundamental information favors our understanding of gasifier operation and design as well as assisting the scientific knowledge to expedite the practical use of the gasification technique. In the future, large-scale studies of this process should be carried out to prove its commercial applications.

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