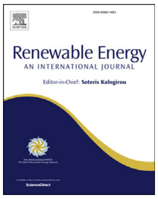
Renewable Energy 109 (2017) 135–143

Contents lists available at ScienceDirect

Renewable Energy

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



Effects of different operating parameters on the syngas composition in a two-stage gasification process

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A R T I C L E I N F O

Article history:
Received 5 May 2016
Received in revised form
2 February 2017
Accepted 8 March 2017
Available online 9 March 2017

Keywords:
Two-stage gasifier
Equivalence ratio
Steam/biomass
Syngas

A B S T R A C T

This research used a two-stage fluidized-bed gasifier to investigate the effects of the temperature, equivalence ratio, and steam/biomass ratio on the syngas composition. When the operating temperature in the first stage increased from 700 °C to 900 °C, the proportion of H_2 in the syngas increased significantly. After passing through the second stage (900 °C), the syngas produced from the first stage underwent the thermal reaction again, and the proportion of H_2 was further increased. When the ER value increased from 0.2 to 0.3, the proportion of H_2 in the syngas increased; whereas, when the ER value increased to 0.4, the amount of H_2 produced was reduced. For S/B ratio, an increase to 0.5 enhanced the steam content of the gasifier and accelerated the methane–steam reforming reaction, thus producing more H_2 (up to 52 mol%). Furthermore, when the operating temperature of the fluidized bed reactor at the second stage was set at 900 °C, the proportion of H_2 in the syngas could still be effectively improved to more than 42 mol% although the operating temperature at the first stage was only 700 °C. The proportion of H_2 was enhanced to more than 52 mol% with a combination of appropriate ER and S/B ratio values.

1. Introduction

Taiwan currently has 24 large incineration plants in operation, and nearly 600 million tons of waste can be processed each year. Since 2008, the disposal rate of municipal solid waste in Taiwan has been 99.9%; except for recycling, 97% of the remaining wastes are processed by incineration [1]. However, with increasing resource scarcity and the rise of the “zero waste” concept, waste has been increasingly considered as another resource. Since the majority of recycled waste is organic matter, the transition from incineration to gasification of wastes can not only solve the problem of waste disposal, but also produce reusable energy. With gasification technologies, organic materials are converted into reusable syngas (e.g. a mixed gas comprising CO, CH_4, and H_2) via partial oxidation for further purification and application. Generally, the common gasification operating parameters include the type of biomass, temperature, pressure, feed particle size, particle size of the bed material, type of gases, equivalence ratio (ER), and steam/biomass (S/B) ratio [2–5]; the operating temperature, ER, and S/B ratio all exhibit significant impacts on the syngas composition from the gasification process.

In the gasification process, the operating temperature directly affects the gasification reaction. A temperature increase changes the surface temperature of the bed material so that there is an improvement in the thermal conductivity between the bed material and biomass, thereby affecting the product gas composition and heating value. Kumar et al. [4] investigated the effect of operating temperatures in the range of 650–850 °C on gasification and found that the highest carbon conversion efficiency (82%) and energy conversion efficiency (96%) were obtained at 850 °C; the H_2 concentration increased from 4% at 650 °C to 15% at 850 °C. A study by Luo et al. [6] suggested that when the vaporization temperature increased from 600 °C to 900 °C, the carbon conversion efficiency and the amount of gas generated increased from 61.96% to 92.59% and from 1.15 Nm^3/kg to 2.53 Nm^3/kg, respectively. Furthermore, findings from Gómez-Barea et al. [7] also revealed that when the operating temperature was in the range of 820–1200 °C, an increase in operating temperature could increase the gas production rate from 67% to 81% and reduce the tar yield. Gao et al. [8] and Ma et al. [9] also addressed that an increase in operating temperature could increase the amount of H_2 in the syngas. Luo et al. [6] suggested that an operating temperature increase could intensify the

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http://dx.doi.org/10.1016/j.renene.2017.03.019
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water–gas shift reaction, and Boudouard reaction, resulting in the production of more H_2 and CO; the reaction mechanism is as follows:

Water–gas shift reaction

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{1}$$

Boudouard reaction

$$C + CO_2 \leftrightarrow 2CO \tag{2}$$

Another important parameter in the gasification process is ER, which is the ratio of the actual air–fuel ratio and the stoichiometric air–fuel ratio. It is an essential parameter indicative of whether there is complete oxidation in the gasification process. Lv et al. [10] investigated the impact of ER adjustment upon the product gas composition in the gasification process. When ER was increased to 0.27 from 0.19, the proportion of CO_2 gas in the produced gas showed an upward trend and those of CO and H_2 were slightly decreased. Hence, when ER is increased, the amount of oxygen that enters the gasifier and undergoes the reaction also increases such that the carbon conversion efficiency is enhanced, the CO_2 production is increased, and the CO and H_2 productions decrease. A study by Chiang et al. [11] showed that after the ER value increased, the amount of oxygen in the gasifier increased, and the combustion efficiency improved. When the ER value increased from 0.2 to 0.3, the difference between the H_2 production and the productions of CO_2 and CO was small; however, when the ER value increased to 0.4, the CO_2 production increased by 10%, and the productions of CO and H_2 decreased by 8% and 3%, respectively. Gregorio and Zaccariello [12] found that when the ER value increased from 0.26 to 0.31, except for increased CO_2 production, the productions of CO, H_2, CH_4, and tar all decreased. Based on the results of previous studies, an appropriate ER value for the gasification process should be controlled in the range of 0.2–0.4 [5].

The S/B ratio is the ratio of the amount of steam to the amount of biomass feed in the gasifier and is also an important parameter affecting gasification. A study by Ruiz et al. [13] showed that when the gasification temperature was maintained at 750 °C whilst increasing the S/B ratio, the productions of CH_4, H_2, and CO_2 gradually increased, while CO production decreased. A study by Dascomb et al. [14] suggested that when the S/B ratio increased from 0.7 to 4.5 and the temperature was maintained at 850 °C, H_2 production increased by 10%, but the energy conversion efficiency decreased from 68% to 42%. Furthermore, Wang et al. [15] also found that an increase in the S/B ratio (0.0–1.23) led to increases in the total gas yield and H_2 production as well as a decrease in the tar production. As an increase in the S/B ratio can increase the amount of H_2 participating in the gasification process, an increase in H_2 production via enhancement of the S/B ratio was observed. However, the S/B ratio should be controlled within a certain range, otherwise excessive water vapor may absorb heat inside the gasifier, thereby causing the gasification reaction to not proceed efficiently owing to the temperature decrease.

Currently, numerous studies have focused on modifying the gasifier design to enhance syngas production, in order to increase the value of syngas for reuse. Tar, char, and other challenges can still simultaneously occur in the gasification process using fluidized-bed gasifiers; consequently, the two-stage gasification process is a relatively new technology. In a study by Soni et al. [16], waste from the slaughtering industry was employed as raw material to conduct oxidation, and the reactors of the first and second stages were fixed-bed gasifiers. The difference between the first stage and the second stage gasification processes was compared, and the results suggested that the second-stage oxidation could effectively enhance the H_2 yield (7.3%–22.3%) and total gas yield (30.8%–54.6%); moreover, the tar yield decreased from 18.6% to 14.2%. Xiao et al. [17] used woodchips and other biomass as raw materials to conduct the second-stage gasification, and the syngas, tar, and additional products from the first-stage gasification reaction entered the second-stage reactor to undergo reactions. In contrast, tar and char were burned or cracked in the second-stage reactor, and the discharge of tar and char was reduced. In a study by Park et al. [18], two fixed-bed reactors were utilized for two-stage gasification, and there were complex hydrocarbons in the tar generated from the first stage. The tar entered the second-stage reactor to undergo a cracking reaction, and the possible reactions are as follows [18,19]:

$$C_nH_x \rightarrow C_mH_y + H_2 \tag{3}$$

$$C_nH_x + H_2O \rightarrow H_2 + CO \tag{4}$$

$$C_nH_x \rightarrow Coke + Other\ gases \tag{5}$$

As the fluidized bed reactor has advantages such as high heat transfer and high mass transfer efficiencies, its application in gasification will help enhance the overall gasification efficiency. Accordingly, if the two fluidized bed gasifiers are series-connected to conduct the two-stage gasification process, the gasification efficiency will improve, the generated tar will decrease, and the H_2 production rate will increase. In this study, two-stage fluidized bed gasifiers were employed, and the operating temperature of the first-stage fluidized bed reactor, ER, and S/B ratio were changed to investigate their impact on the product gas composition from the second-stage fluidized bed gasification.

2. Experimental methods

In this study, a laboratory-scale, two-stage fluidized bed gasifier was adopted, and the structural diagram is shown in Fig. 1. The gasifier was made of stainless steel (AISI-310), with a thickness of 0.49 cm and a height of 50 cm; the outer diameter of the gasifier body was 4.27 cm and the inner diameter was 3.29 cm—the specifications were the same for the gasifier bodies of the first and second stages. A stainless steel distributor plate (Perforated mesh plate) was installed at the bottom of each fluidized bed reactor, with an open area of 15.2%. Although the distributor design is not entirely in compliance with the recommendations of Geldart and

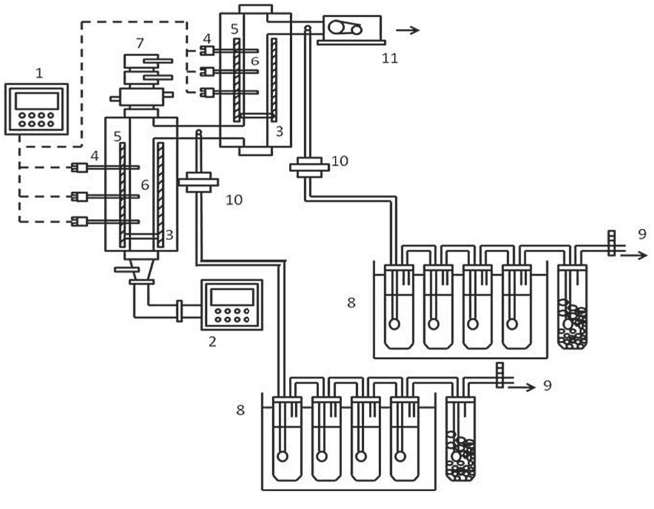

Fig. 1. Two-stage bubbling fluidized bed gasifier. 1. PID controller, 2. Mass flow meter, 3. Distributor, 4. Thermocouple, 5. Electric heater, 6. Gasifier, 7. Manual feeder, 8. Impingers and cooling system, 9. Sampling pump, 10. Glass filter, 11. Induced fan.