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Gasification and tar removal characteristics of rice husk in a bubbling fluidized bed reactor

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ABSTRACT

Technology for converting biomass such as rice husk into a useable energy sources are key to address energy consumption issues. The effects of temperature (600–900 °C), equivalence ratio (ER, 0.15–0.3), and addition of catalyst on the gasification characteristics of rice husk were investigated in a bubbling fluidized bed reactor with an inside diameter of 0.067 m and a height of 1.55 m. As the reaction temperature and ER were increased, the concentrations of CO and CO_2 in the product gas decreased. Slight increases in CH_4 and H_2 concentrations were also observed with increasing temperature. Throughout the temperature range of interest, an increase in ER resulted in decrement of both the higher heating value of the product gas and the cold gas efficiency. Furthermore, the effect of operating condition and addition of bed material were determined in a bubbling fluidized bed reactor. An increase in reaction temperature and ER decreased the tar content. The addition of calcined dolomite and olivine in the bed material reduced the amount of tar during rice husk gasification in a bubbling fluidized bed reactor. These results have the potential to be applied to the conversion of biomass into a useable energy source.

1. Introduction

Owing to the continuously increasing use of high-end technologies in industry, energy consumption is also growing worldwide. In response to the price fluctuation of fossile fuels and more stringent environmental laws and regulations, the major energy-consuming countries are investing extensively in research efforts to convert sustainable biomass sources into eco-friendly energy sources [1].

Among the various sources of biomass, agricultural byproducts such as rice husk and straws are produced worldwide in huge quantities, amounting to 470 million tons per year. Rice husk accounts for 20% of the weight of the rice plant, and 94 million tons of rice husk are produced globally every year [2].

While rice husk has been traditionally used in low value applications such as stall mats, cement filler, and compost, its potential as a high value added material is attracting increasing attention. For example, it has recently been used as a feedstock for gasifiers and boilers to generate heat and electricity in co-generation systems, and can be used as a mineral source for the anode material of Li-ion batteries, solar cells, and nanostructured silicon [3].

Thus, technologies for converting biomass into a useable energy source can be categorized into three main categories: (i) biological methods, such as anaerobic digestion and alcoholic fermentation; (ii) thermochemical methods, such as gasification and pyrolysis; and (iii) physical methods, such as extraction and solidification [4]. For example, the gasification process is a technology that produces a product gas composed mainly of carbon monoxide (CO) and hydrogen (H_2). This is accomplished by the partial oxidation of carbon-containing materials, such as biomass, coal, and petroleum coke. Examples of gasifying agents include oxygen, steam, and carbon dioxide. Using the product gas mixture, numerous products can be manufactured, including chemical substances ranging from ammonia and methanol to industrial gases [5,6]. In terms of the biomass gasification process, important operation parameters include the equivalence ratio (ER), gasifying agent, bed temperature, and catalyst.

The ER can be defined as the oxidizer to biomass mass ratio divided by the stoichiometric oxidizer to biomass ratio. An ER equal to 1 represents theoretically complete combustion. In the

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gasification environment, higher ER values tend to result in lower yields of H_2 and CO, and higher yields of CO_2. The appropriate ER value reported to date for gasification is approximately 0.2–0.3 [7].

Gasifying agents include air and steam, which are commonly used in the biomass gasification process. Despite the use of steam yielding a product gas with higher calorific value than when air is used, steam has one main disadvantage, in that heat needs to be continuously supplied to the gasification reactor to supply steam [8,9].

Bed temperature is also a key in determining the gasifier performance, given that reactions involving C–H_2O and C–CO_2 (i.e., the main gasification reactions) are endothermic. Theoretically, the higher the temperature, the higher the yield, however, the reaction temperature tends to be limited by constraining factors such as reactor material, ash fusion temperature, tar generation and the generation of contaminants, such as NO_x [8,9]. The optimal operating temperature concerning aforementioned constraints appears to be 750–800 °C [10].

Tar produced during gasification can lower the reactor performance and trigger an abnormal pressure build-up by precipitating inside the reactor and at joints, or by entering the turbine pump [11]. Tar, which contains aromatic compounds comprising 1–5 benzene rings along with oxygen-containing and polycyclic aromatic hydrocarbons, is generated in large quantities during biomass gasification. It has a complicated structure and exists as an aerosol under certain conditions, tending to agglomerate with flying particles, or continuing to react further to form polymers [12–15].

However, tar can be removed by controlling reaction and operating condition or by decomposition with additives placed in the reactor bed or at the rearward end. For thermochemical techniques using the latter of these techniques, the use of catalysts such as Ni–Al- and Ni–Ca-based catalysts and fluid catalytic cracking (FCC) catalysts, or additives such as limestone, dolomite, and olivine, is being extensively researched [13,14]. The mechanism of the dolomite reaction in biomass gasification is yet to be clarified; moreover, dolomite is prone to fracture and wear and has a high CO_2 concentration (~48 wt%). Therefore, it should be employed in the form of calcined dolomite after CO_2 removal at high temperatures [8,16,17].

To develop a reliable rice husk gasification process, it is necessary to use a bubbling fluidized bed (BFB) reactor, which is flexible in terms of raw materials and has a superior heat transfer rate. In addition, rice husk gasification behaviors should be thoroughly understood for optimal operation and control of the gasifier, for the design of new gasifiers, and for device scale-up [18]. Additionally, a high efficiency biomass gasification process should be developed by improving the operating conditions through the introduction of tar removal technology.

Table 1 summarizes previous studies on gasification using a BFB [18–24]. Although gasifiers are already commercially used, only a small number of studies have been conducted on biomass gasification, and even fewer studies have derived ER values in the reactor, or have investigated the effects of direct catalyst addition.

In the present study, the effects of temperature (600–900 °C), equivalence ratio (ER, 0.15–0.3), and addition of catalyst on the gasification characteristics of rice husk were determined in a bubbling fluidized bed reactor with an inside diameter of 0.067 m and a height of 1.55 m.

2. Materials and methods

2.1. Materials

Rice husk obtained from Gongju, South Korea, was used as the fuel material. As shown in Table 2 [25], rice husk has low density (ρ_s = 505 kg/m^3) and low sphericity (0.19), and so it has unfavorable

Table 1
Summary of previous studies on biomass gasification.

Author	Reactor/fuel	Temperature (°C/pressure)	Equivalence ratio (ER)	Gasifying agent	Catalyst	Remarks
Kumar et al. [19]	Fluidized bed/Dried Distillers grains with solubles (DDGS)	650–850/ambient	0.07, 0.15, 0.29	Air/steam mixture	N/A	Increasing the ER decreased the hydrogen content but increased carbon conversion and energy efficiency
Lv et al. [20]	Fluidized bed/pine sawdust	700–900/ambient	0.19–0.27	Air/steam mixture	N/A	The higher temperature contributed to increased hydrogen production, but too high a temperature lowered the gas heating value. The LHV of the fuel gas decreased with ER. The optimal value of ER was found to be 0.23
Ghassemi and Shahsavan-Markadeh [21]	Fluidized bed/pine sawdust	600–1400/ambient	0–0.5	Air	N/A	Increasing the ER increased the heating value of syngas, due to a decrease in of H_2 as a valuable gas The cold gas efficiency exhibited a maximum at ER = 0.29. This is due to the increase in gas yield
Guo et al. [22]	Downdraft/corn stalk	900/ambient	0.18–0.37	Air	N/A	The LHV and cold gas efficiency were good with an ER of 0.25–0.27, and a low tar yield of 0.5 g/N m^3 was achieved by increasing the ER
Pfeifer et al. [23]	Dual fluidized bed/wood pellet	750–900/ambient	0.3–0.9	Air/steam mixture	Olivine, FCC catalyst	The temperature range for the catalytic reactions should be from 800 to 900 °C to obtain high conversion rates
Rapagna et al. [24]	Almond shell	700–820/ambient	Unknown	Steam	Olivine, calcined dolomite	The catalytic activity of the olivine and calcined dolomite mixture exhibits a maximum at 800 °C
Narvaez et al. [18]	Bubbling fluidized bed/Pine sawdust	750–850/ambient	0.20–0.45	Air	Calcined dolomite	Increasing the ER from 0.20 to 0.45, decreased the heating value by ~2 MJ/N m^3 and the tar yield by ~50 wt%