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Analysis of syngas production rate in empty fruit bunch steam gasification with varying control factors☆

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ABSTRACT

Biomass gasification is a prevailing approach for mitigating irreversible fossil fuel depletion. In this study, palm empty fruit bunch (EFB) was steam-gasified in a fixed-bed, batch-fed gasifier, and the effect of four control factors—namely torrefaction temperature for EFB pretreatment, gasification temperature, carrier-gas flow rate, and steam flow rate—on syngas production were investigated. The results showed that steam flow rate is the least influential control factor, with no effect on syngas composition or yield. The gasification temperature of biomass significantly affects the composition of syngas generated during steam gasification, and the H_2/CO ratio increases by approximately 50% with an increase in temperature ranging from 680 °C to 780 °C. The higher H_2/CO ratio at a lower gasification temperature increased the energy density of the combustible constituents of the syngas by 3.43%.

Introduction

Fossil fuel depletion is primarily attributed to the enormous energy demand of modern civilization, which has resulted in excessive carbon dioxide emission and unprecedented global warming. Many attempts have been made to avert global warming crises through the increased use of renewable energy, such as solar, wind, and geothermal energy. However, almost all renewable energy sources have drawbacks associated with their intermittent power output, which is dependent on the weather and season, and their topographical limitations regarding construction site. By contrast, biomass is a cheap and abundant source of energy that has good synergy with current fossil fuel power plants. With the objective of mitigating carbon dioxide emission, several research groups have examined the possibility of using biomass to replace at least a portion of current fossil fuel consumption [1].

The direct burning of biomass has several disadvantages, such as low heating value, high moisture content, corrosion problems, wide particle-size distribution, and low homogeneity [2]. To improve the fuel properties of biomass, many thermochemical and biological process are applied to obtain high-quality fuels from biomass. One of these, gasification is a high-temperature process wherein organic and fossil fuel-based carbonaceous materials are converted into carbon

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monoxide, hydrogen, and carbon dioxide with assistance from a gasifying agent. Moisture in the biomass is gradually discharged as the ambient temperature increases to 100 °C, resulting in 5–10% weight loss depending on the type of biomass feedstock [3,4]. As the temperature further increases to 250–400 °C, large carbohydrate compounds, such as starch, hemicellulose, and cellulose, decompose into smaller molecules (e.g., carbon dioxide, methane, acetic acid, and phenol), resulting in major mass loss (approximately 40%). The solid reaction product (char) mostly comprises carbon. Finally, gasification occurs at a high temperature of approximately 650 °C, with the gasifying agents (typically air, because of its low cost) initiating the reaction with carbon in the char and releasing gaseous compounds.

Table 1 presents a list of the major reactions that occur during gasification. The solid residue, called ash, mainly comprises metal oxides. Using oxygen and steam as the gasification agents is expensive and necessitates a complicated gasifier design; however, they produce reaction products with higher heating values than does air. Syngas—which mainly comprises hydrogen and carbon monoxide, with relatively small amounts of methane, carbon dioxide, and other gaseous hydrocarbons such as ethane—is the combustible gas mixture resulting from gasification. The composition of syngas depends on many gasification parameters, such as biomass type, gasification agent, and temperature. Syngas can be used as fuel in internal combustion engines and fuel cells. Biomass gasification can therefore reduce greenhouse gas emission because syngas can partially replace fossil fuels in, for example, hydrogen production [5].

Torrefaction alters the physical and chemical properties of biomass. Torrefied biomass has a relatively higher heating value and lower weight, and is hydrophobic [8]. Torrefaction can thus be considered a means to upgrade the quality of solid biomass, or as pretreatment for gasification. For example, Chew and Doshi [9] reported that a reduction of tar precursors such as acetol and guaiacol was observed after torrefaction of pine. Additionally, they mentioned that torrefaction improved the reactivity of biofuel, thus reducing the required gasifier size. Similarly, other researchers have also reported on enhancing gasification through torrefaction as pretreatment. Deng et al. [10] reported the beneficial effects of co-gasification of coal and torrefied biomass and recommended that small pretreatment factories for torrefaction be built near biomass resources to conveniently obtain high-energy-content char or gas; this gas can subsequently be gasified on a large scale far away from the farmland. Apart from preventing the use of raw biomass, other benefits of torrefaction include simplified milling and enhanced gasifier efficiency due to biomass moisture reduction. Prins et al. [11] reported that pretreating biomass through torrefaction increases the gasification efficiency (exergy balance). Couhert et al. [12] confirmed that pretreating biomass through torrefaction increased the amount of CO and H_2 in gaseous gasification products.

Table 1 – Main gasification reactions [6,7].

Chemical reaction	Kinetics scheme
Boudouard	$C(s) + CO_2 \rightleftharpoons 2CO$
Water–gas (Heterogeneous)	$C(s) + H_2O \rightleftharpoons CO + H_2$
Hydrogenation	$C(s) + 2H_2 \rightleftharpoons CH_4$
Partial oxidation	$2C(s) + O_2 \rightleftharpoons 2CO$
WGS	$CO + H_2O \rightleftharpoons CO_2 + H_2$
Methane reforming (steam)	$CH_4 + H_2O \rightleftharpoons CO + 3H_2$

The use of a gasification agent is another factor that strongly influences gasification. The gasification agent reacts with biomass and breaks it down into gas molecules (notably, the biomass also breaks down under high temperatures through, for example, pyrolysis). Of the many gasification agents, air is the most common; although its oxygen content is only 21%, air is abundant and requires no storage equipment. Pure oxygen can also be used as a gasification agent to increase the heating values of syngas. Once the reaction is initiated, these two gasification agents achieve self-sufficiency, meaning that no external energy is needed. Steam is another agent used for its ability to extract the most amount of hydrogen from biomass; however, it requires additional power input [7]. Occasionally, CO_2 is used as the gasification agent to enhance CO_2 recycling and to reduce CO_2 concentration in the atmosphere.

Several control factors, such as the amount of gasification agent, biomass characteristics, and gasification temperature, affect the outcome of gasification. The effects of these control factors on the products of steam gasification have been extensively investigated. For example, Salmiaton et al. [13] studied the effect of air flow rate, particle size, and gasification temperature on the composition and yield of syngas and reported that a high gasification temperature considerably increased both the yield and heating value of syngas. This increase in heating value is due to the lower CO_2 composition in the syngas at high temperatures. In addition, a smaller particle size slightly increased the syngas production, and an increase in air flow increased the syngas yield but decreased the heating value. Guan et al. [14] examined the effects of biomass type, temperature, and steam flow rate, and found that wood (which is mostly composed of cellulose and lignin) was harder to gasify than was seaweed and that mixing seaweed with wood promoted the gasification reaction of wood. Moreover, introducing a steam flow increased syngas yield, but excessive steam flow decreased the yield because a large steam flow cools the reactor [15]. As was the case in air gasification, a high temperature in steam gasification increased syngas yield.

Many studies have also focused on the time evolution of syngas production. Moon et al. [16] classified the gasification reaction into two, often overlapping, stages: devolatilization and char gasification. In the devolatilization stage, the reaction is limited by the rates of heat transfer and molecule diffusion. Thermodecomposing biomass rapidly produces volatility. In the char reaction stage, the reaction progresses relatively slowly. Overall, Moon et al. reported that high temperatures and steam flow rates promote both devolatilization and char reaction. Wood et al. [17] examined the influence of biomass composition on the gasification of several types of biochar. All biochars exhibited similar two-stage reaction characteristics, and the syngas production time curve varied with the microstructural and elemental composition of the biomasses.