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Parametric analysis of a circulating fluidized bed biomass gasifier for hydrogen production

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ABSTRACT

Biomass is considered a potential energy source which can be efficiently converted to useful gaseous products via a gasification process. Circulating fluidized bed (CFB) gasifiers have attracted significant attention due to their high reaction rates and thermal efficiency. This study aims to investigate the CFB biomass gasification process to generate H_2-rich synthesis gas. A process simulator is used to analyze the gasifier performance by assuming that the gasification is fast and reach equilibrium. Parametric analysis of the CFB gasifier shows that steam gasification generates the synthesis gas attained the highest H_2 content (50–65 vol.%) and the highest product gas quality (higher heating value, HHV = 10–13 MJ/Nm^3) at operating temperatures approximately 650–700 °C. High-temperature steam cannot provide enough energy for the gasifier, reducing the gross cold gas efficiency of this process to only 16%. The biomass air-steam gasification process is investigated while avoiding high energy consumption, but less H_2 is produced under these conditions.

1. Introduction

Energy security becomes the most important issue because energy demand continuously increases while fossil fuel supply declines. Presently, renewable energy sources have been explored to reduce the global dependence on fossil fuels and the emission of greenhouse gases. Consequently, future energy solutions should provide sufficient amounts of sustainable energy with minimal environmental impact.

Hydrogen has been widely discussed as a promising energy carrier because it provides clean and highly efficient energy conversion. This gas can also be used to drive fuel cells for power generation. Currently, many technologies have been developed to produce hydrogen from various sources [1–4]. Agricultural residue is a major resource for renewable energy; it can be converted into various forms of energy through thermochemical or biological processes [5]. The thermochemical processes, including combustion, pyrolysis and gasification, have some advantages over the biological methods because they are more flexible when selecting a feedstock, faster and more efficient [6].

Currently, combustion-based processes are the conventional methods used to convert biomass into heat and electricity; however, the energy efficiency of this process is quite low (20–40%) [7]. Pyrolysis is based on cracking biomass in the absence of oxygen, and the major products are in the liquid phase ("bio-oil") [8]. The commercial application of bio-oil is restricted by their limited use and difficulty during downstream processing [9]. Alternatively, gasification is an attractive means to convert solid fuels (e.g., biomass and coal) to a combustible or synthesis gas [10,11]. This process involves drying, devolatilization and a gasification/combustion process. Currently, different designs for gasification reactors or gasifiers have been proposed. A circulating fluidized bed (CFB) gasifier is a type of gasifier that is currently undergoing rapid commercialization for biomass [12]. This apparatus exhibits

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many advantages during biomass gasification, including a high degree of solid mixing, a high thermal efficiency and good scalability [13].

When operating the gasifier, the quality of synthesis gas is strongly affected by types of used gasifying agents, such as air, oxygen and steam. Air gasification is feasible for industrial applications; however, the synthesis gas produced using this technology has a low H_2 content, which ranges from 8 to 14 vol.%, and a low higher heating value (HHV) approximately 4–6 MJ/m^3 [14]. Although using pure oxygen during gasification can produce gas with a higher heating value (10–18 MJ/m^3), the high cost of pure oxygen generated using current technology, such as a cryogenic air separation, makes the gasification process impractical [9,14,15]. To obtain H_2-rich gas for internal combustion engines, gas turbine systems or fuel cells for electricity and heat generation, steam gasification might be an interesting alternative [16–19] because this process can produce synthesis gas with high H_2 contents (30–60 vol.%) and higher heating values (10–16 MJ/m^3) [14]. However, steam gasification reactions are endothermic, requiring large amounts of energy for the gasifier [20]. Adding air to steam gasification, which is called air-steam gasification, is an alternative for supplying energy based on the partial combustion of biomass with air; however, the quality of the product gas may be lower [11,21].

In general, the composition of the synthesis gas is the major parameter affecting the performance during biomass gasification because it directly affects the heating value of the product gas and the gasification efficiency [6,9]. However, making exact predictions of synthesis gas compositions is not easy because these models depend on many parameters, such as the biomass composition, operating conditions and gasifying agent. Umeki et al. [20] studied on the performance of a high temperature steam gasification process for woody biomass and found that the obtained synthesis gas, which contained 35–55 vol.% H_2, was generated by water–gas and steam reforming reactions. The cold gas efficiency was 60.4%, but the gross cold gas efficiency was 35% due to the heat supplied by high-temperature steam. Mehrdokht and Mahinpey [22] performed a sensitivity analysis of a biomass fluidized bed gasifier, finding that the H_2 content in the product gas increased when increasing the operating temperature. Adding more steam to the gasifier increases the H_2 and CO production while decreasing the CO_2 and carbon conversion. Kumar et al. [23] also studied the effect of operating parameters of fluidized bed gasification, such as gasification temperatures and gasifying agent feed rates, on the energy conversion efficiencies. The results showed that the gasification temperature is the most influential parameter while the gasifying agent feed rates has the strong effect on the carbon conversion and energy efficiencies. The balance between air and steam feed rates was the way to achieve H_2-rich gas production. Doherty et al. [15] developed a model of a CFB biomass gasifier to predict its performance under various operating conditions. The heating value of the synthesis gas increased with the equivalent ratio of the air supply. Preheating the air increased the H_2 and CO contents. Steam was introduced to promote H_2-rich synthesis gas production.

The aim of this study is focused on improving the CFB biomass gasification process to produce a H_2-rich synthesis gas. A model of the CFB gasifier is developed using a commercial process simulator to investigate the effect of key operating parameters, such as the gasifier temperature, steam temperature, steam-to-biomass ratio (S/B), equivalent ratio (ER) and type of gasifying agents, on the performance of the CFB gasifier. The synthesis gas composition and heating value, as well as the biomass gasification process efficiency, are the criteria used to determine suitable operating conditions for the CFB gasifier.

2. Methods

2.1. Model of a circulating fluidized bed (CFB) gasifier

The fluidized bed reactor has been broadly utilized for coal and biomass combustion and gasification. A traditional bubbling fluidized bed gasifier has a lower carbon conversion efficiency; therefore, the design of fluidized bed gasifiers has shifted from low velocity bubbling beds to high velocity circulation-based designs because a circulating fluidized bed gasifier (CFB) has a higher char circulation rate, improving the overall efficiency [24].

Circulating fluidized bed gasifiers might improve biomass gasification by using higher gasifying agent flow rates to entrain and move the bed material, which can be either sand or char; in addition, these apparatuses recirculate nearly all of the bed material and char with a cyclone separator. A schematic diagram of a CFB biomass gasifier is shown in Fig. 1(a). When the biomass is added to the gasifier, it is rapidly dried and pyrolyzed, releasing all of the gaseous portions of the biomass at a relatively low temperature. The remaining char is oxidized within the bed to provide a heat source for the drying and gasification processes. The large thermal capacity of the inert bed material plus the intense mixing associated with the fluid bed allow this system to handle a much greater quantity of material with a much lower quality fuel.

2.2. Process workflow

The CFB gasifier is modeled using a commercial process simulator (Aspen Plus). The model is divided into three stages including devolatilization, gasification and solid recirculation, as shown in Fig. 1(b). The main assumptions made to develop the CFB model are as follows: the process is operated under steady state conditions; the gases are treated as ideal gases; the ash is treated as an inert solid, and tar formation is ignored because of the relatively high operating temperature [25]; the syngas is produced by the gasifier at the chemical equilibrium; heat losses are ignored, the cyclone separation efficiency is 90% [26], and 2% of the carbon is lost to the ash [27].

In Fig. 1(b), the 'BIOMASS' stream was treated as a nonconventional stream whose proximate and ultimate analyses are defined in Table 1 (pine sawdust). The standard operating conditions of this study are shown in Table 2. The 'DECOMP' block is used to represent the devolatilization process, which is a thermal decomposition process for the biomass; the biomass is converted to volatile materials and solids, such as H_2, N_2, O_2, C (carbon), S (sulfur), and ash. The RYield module is ASPEN Plus is used for modeling at this stage after specifying the yield distribution, which is determined based on the ultimate analysis of the pine sawdust (Table 1). The enthalpy of the 'DECOMP' product stream does not equal that of the feed stream. Consequently, the 'Q-DECOMP' heat stream is inserted to balance the enthalpy of the biomass stream.

The product of the thermal decomposition process ('DECOMP' stream) and the recirculating solid carbon ('CRECYCLE' stream) reacts with steam ('STEAM' stream) in the gasification reaction block, which is called 'GASIF1'. The gasification mechanism involves a complex collection of various reactions during a real gasification process; however, the gasification reactions are simplified to 8 major reactions in the present model. These reactions are summarized in Eqs. (1)–(8) [15]. Reactions (1)–(4) are the gasification processes for char particles that produce CO, H_2 and CH_4. Reaction (1) is the partial combustion of C. The generated heat from first reaction is supplied to the endothermic reaction (2), which is the Boudouard reaction, and reaction (3), which is the heterogenous shift reaction. Reaction (4) describes the equilibration of the hydro gasification reaction process, which depends on the volatile matter in the feedstock. The reaction rates of (2)–(4) are known to be slower than that of reaction (1) [31].

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