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SIMULATION OF THE EFFECTS OF THE EQUIVALENCE RATIO ON HYDROGEN PRODUCTION IN FLUIDIZED BED BIOMASS GASIFIERS

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ABSTRACT
In recent years, hydrogen production from biomass has been optimized in fluidized bed conditions, and the steam gasification has become an area of growing interest because it produces a gaseous fuel with relatively higher H_2 content which could be used in fuel cells, a new technology for the future to produce power in a much cleaner manner. The equivalence ratio is one of the most important operating variables in biomass gasification with air. In this work it is defined as the air-to-fuel weight ratio used, divided by the air-to-fuel weight ratio of stoichiometric combustion. The equivalence ratio shows two opposing effects on the gasification process. Increasing the amount of air favors gasification by increasing the temperature but, at the same time, produces more carbon dioxide. Gasification with a better level of efficiency produces more carbon monoxide and less carbon dioxide. From this point of view, in this study, the effects of the equivalence ratio on hydrogen production from an atmospheric biomass fluidized bed gasifier is simulated by developed 2D model. The model simulation results are also compared with and validated against experimental data given in the literature. The model predictions are in a good agreement with experimental data where the maximum error values do not exceed 0.17.
Keywords: fluidized bed, hydrogen, equivalence ratio, simulation, renewable energy

1. INTRODUCTION
Hydrogen is expected to be the most important energy carrier in a sustainable energy system of future society. In order to have environment friendly hydrogen, it must be produced by renewable methods. A number of ways and a variety of resources for producing renewable hydrogen are being investigated in the literature. Of all the renewable resources, biomass holds the greatest promise for hydrogen production in the near future. Thermochemical biomass gasification has been identified as a potential technology for producing renewable hydrogen [1].
The conversion of biomass by gasification into a fuel suitable for use in a gas engine increases greatly the potential usefulness of biomass as a renewable resource. Gasification is a robust proven technology that can be operated either as a simple, low technology system based on a fixed-bed gasifier, or as a more sophisticated system using fluidized-bed technology [2].
Gasification is the conversion of biomass to a gaseous fuel by heating in a gasification medium such as air, oxygen or steam. Unlike combustion where oxidation is substantially complete in one process, gasification converts the intrinsic chemical energy of the carbon in the biomass into a combustible gas in two stages. The gas produced can be standardized in its quality and is easier and more versatile to use than the original biomass e.g. it be used to power gas engines and gas turbines, or used as a chemical feedstock to produce liquid fuels. Strictly, gasification includes both biochemical and thermochemical processes, the former involving microorganisms at ambient temperature under

anaerobic conditions i.e. anaerobic digestion, while the latter uses air, oxygen or steam at temperatures >800°C [2].

As the use of oxygen for gasification is expensive, air is normally used for processes up to about 50 MWth. The disadvantage is that the nitrogen introduced with the air dilutes the product gas, giving gas with a net calorific value (CV) of 4–6 MJ/Nm^3 (compared with natural gas at 36 MJ/Nm^3). Gasification with oxygen gives a gas with a net CV of 10–15 MJ/Nm^3 and with steam, 13–20 MJ/Nm^3. It can be seen that while a range of product gas qualities can be produced, economic factors are a primary consideration. The reaction taking place in the gasifier can be written as follows:

$$\text{biomass} + \text{heat} \xrightarrow[\text{air}]{\text{steam or}} H_2 + CO + CO_2 + CH_4 + C_nH_m + \text{tars.} \tag{1}$$

Here, the heat of reaction *(ΔH_R)* is positive for steam gasification (endothermic reaction) and negative for air gasification (exothermic reaction). The gasifier is the most important component in any biomass gasification system; the correct design and operation of the gasifier results in high gas yields and improved efficiency. Unlike the reaction with air/oxygen, the reaction of carbon with steam (the water gas reaction) is endothermic, requiring heat to be transferred at temperatures around 700°C, which is difficult to achieve. Gasifiers self-sufficient in heat are termed auto-thermal and if they require heat, allothermal: auto-thermal processes are the most common [2].

Fluidized bed gasifiers have been used for converting agricultural wastes into energy. The advantages of fluidized bed reactors include: good gas solids contact, excellent heat transfer characteristics, better temperature control, large heat storage capacity, good degree of turbulence and high volumetric capacity. Several researchers studied the effects of operating and design parameters on the performance of fluidized bed gasifiers theoretically [3]. The existing fluidized bed gasification models can be classified as thermodynamic models, flow regime models and transient models. However, most of these gasification models were reported for coal gasification and those dealing with biomass gasification did not include the hydrodynamic parameters which affect both the mass and heat interchange coefficients between the bubble and emulsion phases [4].

Equivalence ratio (ER) is a measure of the amount of external oxygen (or air) supplied to the gasifier. ER is obtained by dividing the actual oxygen (or air) to biomass molar ratio to the stoichiometric oxygen (or air) to biomass molar ratio. Oxygen is generally supplied as a gasifying and fluidizing medium. Using air in place of oxygen though economical has the negative effect of diluting the product gas due to the presence of nitrogen. The ER is one of the most important operating variables in biomass gasification with air. In biomass gasification, the ER varies from 0.10 to 0.30. The equivalence ratio shows two opposing effects on the gasification process. Increasing the amount of air favors gasification by increasing the temperature but, at the same time, produces more carbon dioxide [5]. From this point of view, in this study, the effects of the equivalence ratio on hydrogen production from an atmospheric biomass fluidized bed gasifier are simulated by developed 2D model. The model simulation results are also compared with and validated against experimental data given in the literature.

2. MODELING

Biomass consists of mainly C, H, N, O, S, Cl, ash, and moisture. Carbon will partly constitute the gas phase, which takes part in devolatilization, and the remaining carbon comprises part of the solid phase (char) and subsequently results in char gasification. The mathematical models for fluidized bed reactors can be divided into three main groups, characterized by the number of phases accounted in the reactor: single-, double- and three-phase model [6]. The double-phase model has been the basis for the present study, with a dense phase (gas plus solid particles) and a bubble phase (mainly gaseous with much lower solid matter) [7]. The details of the fluidized bed hydrodynamic model are given in the literature [7].

The overall process of biomass gasification in the bubbling fluidized bed can be divided into four steps. The first step is drying, where the moisture of biomass evaporates. The second step where volatile compounds in biomass evaporate is called devolatilization. In the model, volatiles are entering the combustor with the fed biomass particles. It is assumed that the volatiles are released along the riser at a rate proportional to the solid mixing rate. The degree of devolatilization and its rate increase with increasing temperature. The details of devolatilization are given in the literature [7]. This is followed by pyrolysis, the step where the major part of the carbon content of biomass is converted into gaseous compounds. The result of the pyrolysis is, apart from gases, a carbon-rich solid residue called char. In the last step, the char is partly gasified with steam and converted into gaseous products. The amount of unreacted char is a function of gasification conditions, such as temperature and biomass particle residence time in the gasifier. The gas stream from the bubbling fluidized bed consists of a mixture of hydrogen, carbon monoxide, carbon oxide and a small amount of methane and tar. All reactions using in the model are given in Table 1. The reaction rates of the reactions are given in the literature [7, 8]

Table 1. Chemical reactions used in the model.

$C+\frac{1}{\Phi}O_2 \rightarrow \left(2-\frac{2}{\Phi}\right)CO+\left(\frac{2}{\Phi}-1\right)CO_2$
$C+\frac{1}{2}O_2 \leftrightarrow CO$
$C+O_2 \leftrightarrow CO_2$
$C+H_2O \leftrightarrow CO+H_2$
$CO+H_2O \leftrightarrow CO_2+H_2$
$CO+3H_2 \leftrightarrow CH_4+H_2O$

The two-phase reactor is modeled as the sum of several elemental reactors of dz thickness. The main steps of the calculation procedures are summarized as follows:

- input of the biomass composition and the oxidizer type, ER, moisture;
- input of the general reactor design parameters: length, diameter, thickness and wall materials;
- calculation of the bed temperature;
- iterative process for each control volume into which the fluidized bed has been divided, involving bed hydrodynamics, heat and mass transfer and gasification kinetics, up to the bed top;
- comparison of the results with experimental data.

In this work it is defined as the air-to-fuel weight ratio used, divided by the air-to-fuel weight ratio of stoichiometric combustion.

3. RESULTS AND DISCUSSION

The ER is one of the most important operating variables in biomass gasification with air. In biomass gasification, the ER varies from 0.10 to 0.30 [5]. The model predictions about the influence of ER on hydrogen production are shown in Fig.1 which also plots the experimental results of Lv et al. [9]. The total height of the reactor is 1.4 m, with a bed diameter 40 mm and a freeboard diameter 60 mm. Silica sand is used as bed material. In this comparison, the same input variables are used in the experiments as

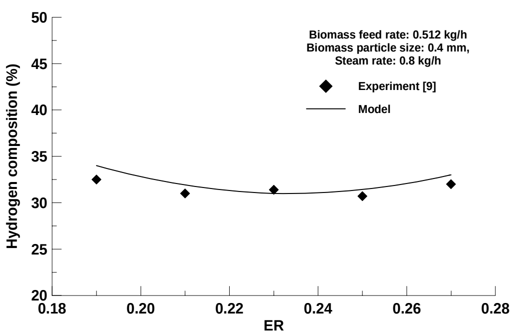

Figure1. Effects of ER on H_2 composition.

the simulation program input. ER is varied from 0.19 to 0.27 through changing the air flow rate and holding the other conditions constant (biomass feed rate: 0.512 kg/h; biomass particle size: 0.4 mm; reactor temperature: 800°C; steam rate: 0.8 kg/h; steam to biomass ratio: 1.56).

Fig.1 indicated that hydrogen content varied little in the range of ER. The model predictions are in a good agreement with experimental data where the maximum error values do not exceed 0.17. ER not only represents the oxygen quantity introduced into the reactor but also affects the gasification temperature under the condition of auto thermal operation. On one side, higher ER will cause gas quality to degrade because of more oxidization reactions. On the other side, higher ER means higher gasification temperature, which can accelerate the gasification and improve the product quality to a certain extent. Therefore the gas composition is affected by the two contradictory factors of ER. Through the analysis on both the experimental data and model results of varying ER, it can be understood that it is unfeasible to apply too small or too large ER in biomass air-steam gasification. Too small ER will lower reaction temperature, which is not favorable for biomass steam gasification. Too large ER will consume more H_2 and other combustible gases through oxidization reaction. So there exists an optimal value for ER, which is different according to different operating parameters.

4. CONCLUSION

In the present study, the effects of the ER on hydrogen production from an atmospheric biomass fluidized bed gasifier are simulated by developed 2D model. The model simulation results are also compared with and validated against experimental data given in the literature. Through the analysis on both the experimental data and model results of varying ER, it can be understood that it is unfeasible to apply too small or too large ER in biomass air-steam gasification. Too small ER will lower reaction temperature, which is not favorable for biomass steam gasification. Too large ER will consume more H_2 and other combustible gases through oxidization reaction. So there exists an optimal value for ER, which is different according to different operating parameters.

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