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Effect of biomass particle size and air superficial velocity on the gasification process in a downdraft fixed bed gasifier. An experimental and modelling study

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ABSTRACT

A one-dimensional stationary model of biomass gasification in a fixed bed downdraft gasifier is presented in this paper. The model is based on the mass and energy conservation equations and includes the energy exchange between solid and gaseous phases, and the heat transfer by radiation from the solid particles. Different gasification sub-processes are incorporated: biomass drying, pyrolysis, oxidation of char and volatile matter, chemical reduction of H_2, CO_2 and H_2O by char, and hydrocarbon reforming. The model was validated experimentally in a small-scale gasifier by comparing the experimental temperature fields, biomass burning rates and fuel/air equivalence ratios with predicted results. A good agreement between experimental and estimated results was achieved. The model can be used as a tool to study the influence of process parameters, such as biomass particle mean diameter, air flow velocity, gasifier geometry, composition and inlet temperature of the gasifying agent and biomass type, on the process propagation velocity (flame front velocity) and its efficiency. The maximum efficiency was obtained with the smaller particle size and lower air velocity. It was a consequence of the higher fuel/air ratio in the gasifier and so the production of a gas with a higher calorific value.

1. Introduction

In most cases the gasification of residual biomass without an important level of homogenisation is carried out in fixed bed reactors. According to Hobbs et al. [1], approximately the 89% of the coal gasified in the world has been processed by means of fixed bed technology. Yang et al. [2] concluded that fixed bed gasification or combustion is the most common technology for the energy use of biomass and solid municipal wastes.

During the biomass combustion or gasification process, this renewable material undergoes different sub-processes. In a first step, biomass is dried up. Then, as the temperature increases, biomass is pyrolyzed and the lignin and cellulose are decomposed into volatile molecules such as hydrocarbons, hydrogen, carbon monoxide and water. Finally, the remaining solid fraction, which is called vegetal char, is oxidised when an excess of oxygen is available (combustion). When combustion is developed with less oxygen than the stoichiometric, vegetal char is gasified by the pyrolysis and oxidation gases. This process is governed by the chemical reduction of hydrogen, carbon dioxide and water by char. The inorganic components in the biomass are not volatilised and remain in solid state as ash.

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In a significant number of research papers, biomass gasification models of different complexity have been proposed looking for a better understanding of the different sub-processes. Generally, the influence of different parameters on the producer gas composition and its temperature at the exit or along the gasifier is evaluated.

Dimensionless models are useful tools to calculate the final gas composition, assuming that the reactions governing the process are in chemical equilibrium. Ruggiero and Manfrida [3] proposed a model based on chemical equilibrium for studying the effect of different parameters such as biomass elemental composition, equivalence ratio, relative humidity, pressure and temperature, on the gasification process. Other models based on chemical equilibrium are presented in references [4–12].

Yang et al. [13,14] presented a two-dimensional transient model simulating the gasification process of biomass and solid municipal waste in a counter-flow reactor. Within the class of one-dimensional transient models, different approaches have been developed. Shin and Choi [15] and Yang et al. [2,16] took into account the diffusive and species conservation terms in all phases, and the heat transfer by conduction in the solid phase. Di Blasi [17] proposed a model very similar to the previous works, without taking into account the radiative heat transfer along the bed. In another paper, the same author [18] presented similar equations in which the thermal conductivity was taken as a cubic function of temperature coinciding with the usual approach for the heat transfer by radiation. Bruch et al. [19] and Shin and Choi [15] showed that in a packed bed biomass gasifier, the heat transfer by thermal conduction was much lower than the heat transfer by radiation due to the low thermal conductivity of wood.

One-dimensional steady state models of fixed bed downdraft gasifiers have been also proposed. Jayah et al. [20] combined an equilibrium model for the combustion and pyrolysis zone with a one-dimensional steady state model for the char gasification zone (reduction) in order to estimate the temperature profile and species composition along the latter zone as functions of design and process parameters. Giltrap et al. [21] and Babu and Sheth [22] presented a similar model focused on the catalytic effect of char on the heterogeneous reactions in the reduction zone.

Based on the same approach, other authors have modelled updraft gasifiers. Souza–Santos [23] developed a one-dimensional steady state model of the coal gasification/combustion process in a fixed bed counter-flow gasifier. Hobbs et al. [1,24,25] and Ghani et al. [26,27] considered a partial or total equilibrium for the gaseous phase and sub-models for the char devolatilisation. They also adopted the heat transfer by convection in the packed bed as described by De Wasch and Froment [28], and Froment and Bischoff [29,30]. Bryden and Ragland [31] modelled biomass combustion in a stationary counter-flow combustor of 20 cm diameter, without considering the heat transfer by radiation in the bed. The model has been used to study the behaviour of the combustor as a function of bed length, intake air temperature, and biomass moisture and particle size.

Corella et al. [32] presented a one-dimensional steady state model of the gasification process in a fluidised bed reactor. They considered the devolatilisation of the fuel, reduction of water vapour by char and the reforming of tars. Corella and Sanz [33,34] extended the model to predict the gas composition, and tar and char contents as a function of controllable process parameters. Hamel and Krumm [35] and Oliva [36] predicted the gas composition and temperature of the different phases through all gasifier length.

A wide range of mathematical models have been presented describing the devolatilisation process. Bryden et al. [37] developed a kinetic model of biomass devolatilisation taking into account biomass drying, moisture recondensation and pyrolysis. The model is based on three parallel primary equations and two secondary equations describing the cracking of tars into char and gases. The relation between biomass particle size and the devolatilisation process has been studied by Hagge and Bryden [38]. Lapuerta et al. [39] presented a model to determine the kinetic constants of the pyrolysis process by fitting experimental thermogravimetric data (typical particle size 500 μm). The model consisted of three parallel first order reactions, which divide the process in three principal stages: biomass drying, thermal decomposition of hemicellulose and cellulose, and thermal decomposition of lignin. Porteiro et al. [40] presented a mathematical description of the thermal degradation of a densified biomass particle in an oxidising atmosphere. Thunman et al. [41] developed a dimensionless model based on the conservative equations completed with experimental data in order to predict the gas composition for any solid fuel.

Heat transfer by radiation plays an important role in the drying and devolatilisation of biomass in a co-current fixed bed gasifier. In this type of reactors, as the air and biomass flow in the same direction, the gas passes to the char reduction zone, and does not heat the incoming biomass by convection. According to Bruch et al. [19], the heat transfer by radiation is a complex phenomena, as absorption, reflection and emission of radiation are interacting. Depending upon its temperature, area and emissivity coefficient, each particle emits a certain quantity of heat to its surroundings. On the other hand, for solid fuels with a very low conductivity coefficient, as is the case for lignocellulosic biomass, the heat transfer by conduction is smaller in comparison with the heat transfer by radiation. Modest [42] described the deduction of a one-dimensional model for the radiation in a participative medium, and presented several approximate solution methodologies for this phenomenon, e.g. Schuster–Schwarzschild approximation. This model was applied by Gosman and Lockwood [43] to develop a two-dimensional model of a gas burner. Argento and Bouvard [44] determined the radiative properties of a porous medium by means of a one-dimensional steady state model. The model was used to determine the intensity of radiation within the medium in both directions (forward and backward) depending principally on the absorption and dispersion coefficients of the porous medium.

The main goal of this paper is to develop a one-dimensional steady state model for the gasification process of biomass in a fixed bed downdraft gasifier. This model, validated using experimental data obtained in a lab-scale gasifier [45], can simulate the dynamic behaviour of stratified downdraft gasifiers. The stationary approach allows an improvement in the integration precision through the all process; while the integration of the differential equations