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Modeling particle population balances in fluidized-bed wood gasifiers

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ABSTRACT

An unsteady model is developed for the particle size distribution in fluidized-bed reactors including fragmentation, abrasion, elutriation and the chemical reactions of wood gasification. Based on the assumption of constant conditions (gas composition, temperature, velocity) of the surrounding atmosphere, an analytical solution is developed for the distribution of sizes belonging to the classes of mother and fine particles. It is found that for the typical feed sizes (minimum above 3×10^{-2} mm) and the usual maximum size of fine particles (2.4×10^{-3} mm), the behavior of fine particles is quasi-steady with respect to mother particles. The numerical solution of the quasi-steady formulation of particle population balances is also coupled with a two-phase (bubble and emulsion), three-zone (bed, splash zone and freeboard) model for a bubbling fluidized-bed reactor, giving predictions of the producer gas composition in agreement with measurements for air gasification of wood.

1. Introduction

Biomass is the only widespread source of renewable energy and carbon. Increased use of this fuel can contribute in reducing carbon dioxide emissions and enhance energy security. Thermo-chemical conversion has attracted significant interest, in particular gasification, as homogeneous, gas phase combustion of syngas can be more efficient and easier to control than solid fuel combustion. Fluidized-bed gasifiers present the advantages of good temperature control, low-medium tar yields, toleration of variation in the feed quality/size, partial load operation, easy start-up and shut-down and high conversion efficiency although the particulate content in the gas and the carbon loss with ash are higher than for fixed-bed reactors [1]. As pointed out in Ref. [2], the implementation of commercial plant technology traditionally foresees comprehensive experimental investigation, progressing from laboratory scale test units to a pilot-scale plant, before a commercial demonstration plant can be built. In order to optimize the process, extensive experimentation is required for the various scales about the effects of operating and design parameters. This optimization procedure can be speeded up and become less expensive with the aid of mathematical models, on condition that the equation formulation includes all the important chemical and physical processes by describing their mutual interactions and the dependence on the process parameters.

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Several transport models have appeared [3–12] for biomass gasification in bubbling fluidized beds, which couple the well known two-phase hydrodynamics with global kinetics, mass and, in a few cases, heat transfer. However, none of them takes into account the distribution of bed particles (particle population). This affects and is, in its turn, affected by the bed hydrodynamics, the extent of chemical reactions, attrition, elutriation and the heat and mass transfer rates.

A great effort has been made in the formulation and solution of particle population balances essentially in the field of coal conversion [13–19] with the exception of Khan et al. [20,21] who consider a fluidized-bed biomass combustor, but a comprehensive unsteady model is still lacking. The models currently available are for a large part for steady-state conditions [13,14,16–18,20,21] using several simplifying assumptions. The unsteady models are based on either an analytical solution [19] or a numerical solution by means of the orthogonal collocation method [15] but attrition of the particles is never taken into account for char, although the treatment proposed for other materials, such as limestone [22], could be extended to the problem under study.

Two main mechanisms of size reduction for carbonaceous particles in fluidized beds are reported [23]: abrasion, where particles of much smaller size break away from the original particle, so that particles become slightly smaller than the original ones, and fragmentation, where the breaking-away process gives rise to a number of particles of smaller size than the original ones. Biomass particles and, in a special way, char particles, generated from the pyrolysis stage, undergo size reduction not only as a consequence of the reactions but also owing to fragmentation and abrasion. The attrited fines can be easily elutriated away unreacted, reducing the process efficiency. For instance, it is pointed out [17] that if a combustor is optimally designed or operated, each 1% efficiency improvement would mean a tremendous cost saving for a power plant.

This study consists of two main parts. In the first part, a comprehensive unsteady model of particle population balance in fluidized-bed gasifiers is proposed. The particle distribution is divided into two size ranges: the class of fine particles contiguous to the class of mother particles. This approach is supported by a number of previous studies [17,18,20,21] and is justified by the fact that there are no significant amounts of intermediate-sized particles between the mother particles and the fines produced from the former by abrasion. Based on the assumption of constant conditions of the surrounding gas, analytical solutions are developed of the model equations for the two size ranges which are used for a parametric analysis with the scope of identifying the processes/parameters which play a controlling role. Also, the conditions are determined which permit a quasi-steady approximation for the behavior of fine particles with respect to the class of mother particles. In the second part of the study, using the analytical solution as a benchmark, a numerical solution is implemented of the quasi-steady version of the model. This is incorporated in a state-of-the-art model for an isothermal bubbling fluidized bed biomass gasifier schematized according to the two-phase theory of fluidization. The coupled particle population balance and the fluidized bed models are used to simulate gasification of wood with air at a laboratory scale obtaining good agreement between measured and predicted gas composition.

2. Mathematical model

The unsteady, one-dimensional mathematical model for the bubbling fluidized bed is formulated in accordance with the two phase theory of fluidization [24], with the existence of an emulsion and a bubble phase, and introducing three spatial zones corresponding to bed, splash zone and freeboard, which are isothermal. The gasifying agent is injected from the bottom while the biomass particles are fed at a certain bed height. The gas phase behaves according to the ideal gas law and is at a constant pressure. The emulsion phase, consisting of an interstitial gas phase at the conditions of minimum fluidization and a solid phase, is assumed to be perfectly mixed. The fuel particles do not contribute in the definition of the void fraction and solid mass of the emulsion phase, given that they are only a small percentage compared with the inert particles. However, their size distribution (and mass) is determined by means of a population balance. The bubble phase consists of gas only and is described by a plug-flow approximation.

A plug-flow approximation is used for the splash and freeboard zones. These, in addition to the gas phase, foresee the presence of a solid phase due to char particle elutriation from the emulsion phase: the particle size is constant and equal to the average value over the size range of the elutriated particles. Also, given the small quantity of solid particles, a unit void fraction and a velocity of the solid coincident with that of the gas are assumed.

2.1. *Chemical reactions and moisture evaporation*

Biomass pyrolysis gives rise to a huge number of chemical compounds which, for engineering applications, are often lumped into three groups: permanent gases, tar and char. They result from both primary decomposition of the solid fuel and secondary reactions of vapor-phase organic products into low-molecular weight gases and char, as they are transported through the particle and the reaction environment. The kinetics of biomass pyrolysis has been extensively investigated [25] but, as the characteristic times are shorter by several order of magnitude with respect to those of the heterogeneous reactions of char conversion [26], the process is often assumed to occur instantaneously. This assumption is retained here, approximating primary degradation of wood by means of a global reaction:

$$\mathrm{Wood} \rightarrow \nu_C \mathrm{Char} + \nu_{CO}\mathrm{CO} + \nu_{CO_2}\mathrm{CO_2} + \nu_{H_2}\mathrm{H_2} + \nu_{CH_4}\mathrm{CH_4} + \nu_{H_2O}\mathrm{H_2O} + \nu_{T1}\mathrm{T_1} \quad \text{(a1)}$$

where the gaseous species, water vapor, primary tar (T_1) and char (Char) are formed with assigned stoichiometric coefficients. The stoichiometric coefficients ($\nu_{CO} = 0.035$, $\nu_{CO2} = 0.035$, $\nu_{CH4} = 0.015$, $\nu_{H2O} = 0.20$, $\nu_{H2} = 0.0015$, $\nu_C = 0.215$, $\nu_{T1} = 0.50$) are those corresponding to the yields (%, wt) obtained from the pyrolysis of wood carried out in fluidized beds at temperatures around 800 K [26]. Instead, the thermal