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Advances in mathematical modeling of fluidized bed gasification

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A B S T R A C T

Gasification is the thermochemical conversion of solid fuel into the gas which contains mainly hydrogen, carbon monoxide, carbon dioxide, methane and nitrogen. In gasification, fluidized bed technology is widely used due to its various advantageous features which include high heat transfer, uniform and controllable temperature and favorable gas–solid contacting. Modeling and simulation of fluidized bed gasification is useful for optimizing the gasifier design and operation with minimal temporal and financial cost. The present work investigates the different modeling approaches applied to the fluidized bed gasification systems. These models are broadly classified as the equilibrium model and the rate based or kinetic model. On the other hand, depending on the description of the hydrodynamic of the bed, fluidized bed models may also be classified as the two-phase flow model, the Euler–Euler model and the Euler–Lagrange model. Mathematical formulation of each of the model mentioned above and their merits and demerits are discussed. Detail reviews of different model used by different researchers with major results obtained by them are presented while the special focus is given on Euler–Euler and Euler–Lagrange CFD models.

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1. Introduction and objective

The rapid growth in industrialization all over the world with simultaneous increase in population, air pollution has reached a very critical level, which threatens the public health, deteriorates the environment and damages property and landscape. An alarming deterioration of the quality of the life nullified the advantages gained by a rise in living standards due to industrial development. The problem became so serious that over the last few decades all industrialized and some developing countries introduced increasingly stringent legislation, restricting permissible levels of pollutant emission from major combustion systems such as electricity generating power stations, furnaces and industrial plants as well as by automobiles and aircrafts. Therefore, the conservation of limited supply of fossil fuel, climate change and the increasing concern over global warming prompted a search for a new and clean technology. Amongst the different technologies, one of the most promising future energy technologies is the fluidized bed gasification.

Gasification is the thermochemical conversion of solid fuel into the fuel gas which contains mainly hydrogen, carbon monoxide, carbon dioxide, methane and nitrogen. The product gas from the reactor also contains some contaminants like char particle, ash and some higher hydrocarbons or tar. A limited supply of oxygen, air, steam or a combination of these serves as gasifying agent. The gasification consists of four different steps e.g. drying, pyrolysis or devolatilization, combustion or oxidation and gasification or reduction. These four steps are described below.

1.1. Drying

Drying occurs at about 100–200 °C when the moisture from the solid fuel is driven out and converted into vapor. The solid fuel in this stage is not decomposed because the temperature is not high enough to cause any chemical reaction.

1.2. Pyrolysis or devolatilization

This is a thermal decomposition process where the dried solid fuel is decomposed into low to high molecular weight volatiles including tar and solid charcoal in the absence of oxygen. The pyrolysis or devolatilization reactions are endothermic and thus the heat needed for these reactions is supplied from the combustion or oxidation reactions.

1.3. Combustion or oxidation

The products of the pyrolysis or devolatilization process are partially oxidized by oxygen supplied through air, and then from carbon monoxide, carbon dioxide and water vapor or steam. As the combustion reactions are exothermic and other reactions in gasification are endothermic, the overall heat required for endothermic reactions is supplied by this combustion or oxidation process.

1.4. Gasification or reduction

In gasification step several reduction reactions occur in absence of oxygen because oxygen is consumed in the combustion reactions. These reduction reactions are mostly endothermic. The final products from these reactions are mainly gas mixtures including hydrogen, carbon monoxide, carbon dioxide and methane.

Most of the time drying, pyrolysis or devolatilization, combustion or oxidation and gasification or reduction steps are not separated but they are overlapped in gasification process. For example, in case of large particle, these steps can take place simultaneously. When the large particle is heated up, the outside portion is dried and devolatization also starts. In the core, the particle is still cooler. When the center of a large particle is heated up, too, and drying and devolatization already started on the outside of the particle, the residual char is likely to be already gasified.

In order to investigate the gasification process, different types of gasifiers are developed like updraft gasifier, downdraft gasifier, cross draft gasifier, bubbling fluidized bed gasifier, circulating fluidized bed gasifier, twin fluidized bed gasifier, entrained flow gasifier etc. Detailed descriptions of the gasification technologies are available in the literature [1,2]. Amongst the different types of gasification technologies, the fluidized bed technology has a number of advantages which include but not limited to the high heat transfer, uniform and controllable temperature, favorable gas–solid contacting, higher efficiency and fuel flexibility.

In order to analyze the process of fluidized bed gasification, several modeling approaches have been deployed and they are broadly classified into two groups; equilibrium modeling and rate base or kinetic modeling. Equilibrium modeling is independent of the type of gasifier because it does not consider the hydrodynamic of the bed. Depending upon the process of calculating the product gas composition, the equilibrium model may be classified as the stoichiometric equilibrium model or non-stoichiometric equilibrium model. Whereas, the kinetic model generally consider the hydrodynamics of the bed coupling with the reaction kinetics. Based on the hydrodynamic modeling, the fluidized bed models can also be classified as two-phase flow model, Euler–Euler model and Euler–Lagrange model. In hydrodynamic modeling, the most established model is the two-phase flow model. Very recently, the computational fluid dynamic (CFD) modeling of fluidized bed gasification based on Euler–Euler approach and Euler–Lagrange approach are attempted by researchers due to the increasing computational power of the modern computers. But, application of CFD model to study the fluidized bed gasification process is in the developing stage and more studies are needed [3,4]. In the present work, a detailed review of different fluidized bed gasification models published in the literature is presented. Mathematical equations governing fluid and solid flow, heat and mass transfer and chemical reactions for each model are presented. Advantages and disadvantages of different modeling approaches and major results obtained are discussed. The special attention has been given to the recently published Euler–Euler and Euler–Lagrange CFD models.

2. Fluidized bed gasifiers

There are different types of fluidized bed gasifiers reported in the literature. Amongst them, a detailed description of the bubbling fluidized bed gasifier, the circulating fluidized bed gasifier and the twin fluidized bed gasifier are presented here. Fig. 1 shows the