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Modeling of hydrodynamics in a bubbling fluidized-bed gasifier and evaluation of the inter-phase gas exchange rate under different operating conditions

Bijoy Das[a], Amitava Datta[b,*]

[a] Development Consultants Pvt. Ltd, Salt Lake City, Kolkata 700 091, India
[b] Department of Power Engineering, Jadavpur University, Salt Lake Campus, Kolkata 700 098, India

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ABSTRACT

A fluid dynamic model of a bubbling fluidized-bed coal gasifier is presented considering two-phase theory of fluidization. The effects of the gasifier temperature and bed particle size on the hydrodynamic characteristics of both the bubble and emulsion phases of the gasifier bed are studied. The bubble diameter, bubble velocity, and bubble area fraction are evaluated for the bubble phase, whereas the gas velocity and porosity are studied for the emulsion phase, along the height of the bed. Finally, the rate of inter-phase gas exchange from the emulsion phase to bubble phase is calculated under different operating conditions.

Introduction

The power industry is largely dependent on fossil fuel resources around the world. However, limited reserves of resources and the emission of various pollutants from fossil fuel combustion necessitate the adoption of sustainable technology with higher conversion efficiency, reduced emissions, and wide fuel flexibility. Against this backdrop, clean coal power generation technologies are gaining popularity as possible alternatives (Basu, Acharya, & Dutta, 2009). Among the various coal utilization technologies, coal gasification is an attractive alternative for power generation because it offers higher efficiency and improved environmental performance compared with conventional pulverized fuel technology (Wang & Long, 2014; Guana et al., 2010). Recently, there have been numerous developments and studies related to coal gasification involving combined-cycle power generation for the improvement of efficiency and reduction of pollution (Huang, Fang, Chen, & Wang, 2003; Yoshiba, Izaki, & Watanabe, 2004).

Three types of gasifiers are generally employed for coal gasification, i.e., fixed-bed, fluidized-bed, and entrained-bed gasifiers. Among them, the fluidized-bed gasifier technology has been found to perform better for coal having a high ash content, high ash fusion temperature, and high reactivity (Collot, 2006). India has a huge reserve of coal and is the fifth largest coal-producing country in the world today (BP, 2014). However, Indian coal has a very high ash fusion temperature (above 1400 °C), high ash content (35–40%), high reactivity, and high amounts of silica and alumina in coal ash (Higman & Sharma, 1998). Fluidized-bed gasifiers with a moderate operating temperature (800–950 °C) are the most suitable technology for such coal.

The hydrodynamics of the fluidized bed strongly affect the gasification of coal by influencing the residence time and transport rate. In a bubbling fluidized bed, two distinct phases are evident—an emulsion phase and bubble phase (Davidson & Harrison, 1963). The emulsion phase contains gas and solids, whereas the bubble phase is free of solids and contains only gas. The bubbles in the bed assist solid homogenization and increase the heat and mass transfer rates in the gasifier. The bubbles grow in size along the height of the bed owing to the exchange of gas with the emulsion phase. As a result, there is a change in velocity, which affects the residence time of the particles in the bed, rates of attrition and elutriation, and the rates of transport processes. The development of a fully predictive gasifier model requires detailed knowledge of the bed hydrodynamics (Tamidi, Shaari, Yusup, & Keong, 2011).

The bubbling fluidized-bed hydrodynamics can be modeled using computational fluid dynamics (CFD) simulation, employing the solutions of conservation equations of mass and momentum within the bed. The discrete element method uses molecular

* Corresponding author. Tel.: +91 33 23355813; fax: +91 33 23357254.
E-mail address: amdatta_ju@yahoo.com (A. Datta).

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Nomenclature

A	area (m^2)
Ar	Archimedes number
d	diameter (m)
D	bubble diameter (m)
F	flow rate (kg/s)
f_{exp}	bed expansion coefficient
g	gravitational acceleration (m/s^2)
H	height of the reactor (m)
N	number of divisions
Q	volume flow rate (m^3/s)
Re	Reynolds number
T	gasifier temperature (K)
U	velocity (m/s)
V	volume (m^3)

Greek letters

ε	porosity
σ	local area fraction
μ	viscosity
ρ	density

Subscripts

air	fluidizing air
b	bubble
bo	bubble at the distributor plate
bm	maximum bubble
e	emulsion
g	gaseous phase
ge	gas in emulsion
mf	minimum fluidization conditions
o	relative to the holes on the plate
p	relative to the solid particles
r	reactor

dynamics to describe particle collisions and the bubble formation and distribution in the bed (Oevermann, Gerber, & Behrendt, 2009; Yu, Lu, Zhang, & Zhang, 2007; Tsuji, Kawaguchi, & Tanaka, 1993; Hoomans, Kuipers, Briels, & Van Swaaij, 1996). This method is computationally expensive and can only be used on a small scale with a limited number of bed particles. The second approach of the CFD solution considers the gas and particulate phases in the bed to form two interpenetrating continua. This approach additionally adopts an Eulerian–Eulerian two-fluid model for solving the hydrodynamics (Enwald & Almstedt, 1999; Yu et al., 2007; Loha, Chattopadhyay, & Chatterjee, 2013). Taking this approach, particle collisions in the bed are modeled applying the kinetic theory of granular flow. This modeling has been adopted to simulate coal gasifier performance and to predict the composition of generated syngas (Armstrong, Gu, & Luo, 2011).

However, owing to the complexity and computational cost of CFD modeling, most coal gasification models for fluidized beds have used empirical correlations to describe the fluid dynamics inside the reactor (Yan, Heidenreich, & Zhang, 1998, 1999; Hamel & Krumm, 2001; Chejne & Hernandez, 2002; Ross, Yan, Zhong, & Zhang, 2005; Chejne, Lopera, & Londono, 2011). These empirical models are based on two-phase theory of fluidization (Davidson & Harrison, 1963). The emulsion phase is assumed to remain under an incipient fluidization condition and excess gas is found to flow in the bubbles. Yan et al. (1998, 1999) considered the contribution of net flow due to coal gasification in addition to the excess gas flow as described above. They showed that the net flow can affect the fluidization condition in the bed and thus the gasifier performance. The bubble size was cited as a critical parameter of the fluidized bed that affects the bubble rise velocity, solid mixing, and inter-phase mass transfer. Hamel and Krumm (2001) emphasized that the parameters calculated from the fluid dynamical model (e.g., upward and downward gas and solid flows, the porosity of the bed, the residence times of gas and solid inside the reactor, and the gas exchange between bubble and emulsion phases) are important boundary conditions for heat transfer, drying, pyrolysis, and reaction rates. Chejne and Hernandez (2002) developed a model using the two-phase theory and predicted the temperature, gas composition, velocity, and different fluid dynamic parameters in the gasifier. The predictions agree well with the experimental data. Ross et al. (2005) implemented a non-isothermal fluidized bed coal gasifier model and showed that the gas mixture temperature follows the trend of the bubble gas temperature along the height of the bed. They attributed this to the large volume of bubble gas flow. The primary heat source affecting the bubble gas temperature was found to be the flow from the emulsion phase to the bubble phase, establishing the importance of such inter-phase transfer. Chejne et al. (2011) further studied the performance of a pressurized fluidized-bed gasifier firing coal by extending their atmospheric pressure model (Chejne & Hernandez, 2002) to a high-pressure condition. They found that the empirical model based on two-phase theory predicts the model parameters reasonably well and evaluates the gasification performance according to the quality of the syngas produced.

All previous papers acknowledged the importance of bed hydrodynamics on gasification. However, none presented explicitly the effects of important parameters, such as the gasifier temperature and bed particle size, on the hydrodynamics of the fluidized bed. In the present work, we developed a fluid dynamic model for the bubbling fluidized bed using two-phase theory and empirical correlations. The bed is considered to be isothermal and at high temperature. The hydrodynamic characteristics of the bubble and emulsion phases in the bed are evaluated at different gasifier temperatures and bed particle sizes to investigate their effects. As parameters of the bubble-phase behavior, the bubble diameter, bubble velocity, and bubble area fraction are evaluated while the emulsion-phase gas velocity and porosity are studied along the height of the bed. Moreover, the rate of gas exchange from the emulsion phase to bubble phase is computed under different operating conditions. This gas exchange is an important boundary condition for the heat transfer, drying, pyrolysis, and reaction rates in the operation of the gasifier (Hamel & Krumm, 2001). However, no previous studies have studied this quantity or showed any parametric effect on it.

Modeling

The bubbling fluidized-bed coal gasifier, modeled in this work, is schematically shown in Fig. 1. The bed is assumed to operate in a steady state and with one-dimensional variation in the axial direction. In the actual gasifier, coal is fed continuously and reacts with air (and/or steam) to produce syngas, which is primarily composed of hydrogen, carbon monoxide, and a small amount of methane along with inert constituents. However, as the present study deals only with the hydrodynamics of the problem, we excluded heat and mass transfer and chemical reactions from the model, and considered the bed as being isothermal at atmospheric pressure. As the practical fluidized-bed gasifier generally operates in the temperature range from 1000 to 1200 K, we used this temperature range in the present study and considered air as the fluidizing medium. Moreover, the bed particle size was varied to study its effect on the bed hydrodynamics and inter-phase mass exchange rate.