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Temperature effects on hydrodynamics of dense gas-solid flows: Application to bubbling fluidized bed reactors

Akhilesh Kumar Sahu, Vasudevan Raghavan*, B.V.S.S.S. Prasad

Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

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A B S T R A C T

In this article, the effects of operating temperature on the hydrodynamics of dense gas-solid flow inside the fluidized bed reactor are investigated systematically. To this end, 3D simulations have been carried out by incorporating the appropriate model parameters and using the well-known Euler-Euler two fluid methodology in ANSYS FLUENT. The methodology is validated against the experimental results available in the literature. Temperature, air velocity and particle sizes are varied systematically. Results show that the variation of minimum fluidization velocity with temperature depends upon the particle size. For small particles (Geldart's group B), the minimum fluidization velocity decreases with an increase in temperature and the trend is reversed when large particles (Geldart's group D) are fluidized. This behavior is explained by analyzing the modification in inter-phase momentum exchange coefficient due to temperature variation. Voidage profiles, particle velocity and bubble characteristics are also seen to be influenced by the thermal conditions of the fluidized bed reactor. Particle axial velocity tends to decrease with an increase in the operating temperature. For group B particles, temperature has negligible effect on bubble size and expanded bed height. On the other hand, bubble size and expanded bed height decrease with an increase in temperature for group D particles.

1. Introduction

Fluidized bed reactors used for coal gasification usually operate in the temperature range of 850 °C - 950 °C. The transport processes involving particles are affected with temperature, even if the particles are inert, like sand particles. If the particles convert to gaseous products when subjected to heat, the transport processes becomes quite involved. However, most of the studies reported on hydrodynamics of gas-solid flows have been performed at ambient temperature. Pattipati and Wen [1] conducted experiments to investigate the effect of temperature on minimum fluidization velocity (U_{mf}) using particle of different sizes belonging to Geldart's group B and group D. They found that U_{mf} decreased with an increase in temperature for group B particles, but the trend was opposite for group D particles. They further suggested that the Wen-Yu [2] correlation was capable of predicting the U_{mf} at elevated temperatures with reasonable accuracy. Botterill et al. [3] also reported similar observations. Subramani et al. [4] measured U_{mf} of several types of particles, belonging to Geldart's group B, over a broad range of temperature and proposed an empirical correlation to estimate the same. Sanaei et al. [5] investigated the hydrodynamic behavior of Geldart's group B particles in a bubbling fluidized bed at elevated temperature using radioactive particle tracking technique. They claimed that the bubble size and particle mean velocity increased with an increase in temperature up to around 300 °C and then the trend reversed when temperature was further increased to 600 °C. Jiliang et al. [6] performed experiments to investigate the effect of bed temperature and particle size distribution on U_{mf} of ash and sand particles, and proposed a correlation. Table 1 presents a few correlations from literature [2,4,6–9] used to estimate the minimum fluidization velocity.

Attempts have been made to quantify the effect of temperature on the bubble size. However, there exists an ambiguity in literature in this regard and the effect of temperature on bubble size has not been well understood. Geldart and Kapoor [10] reported that, for the same excess gas velocity and static bed height, bubble size at 573 K was 15%–25% smaller than the one at the room temperature for steel shots belonging to Geldart's group B size. Sitthiphong et al. [11] used the flow visualization tools to understand the bubble eruption process for group D particles at several temperatures and claimed that the eruption diameter increases with an increase in the operating temperature. The variation in U_{mf} measured by Sitthiphong et al. [11] was significantly different from the U_{mf} estimated using Wen-Yu [2] correlation. Hatate et al. [12] observed for group A particles that, the bubble size was larger at 600 K than at 300 K. On the other hand, Hatate et al. [13] claimed that bubble size remains unaffected due to temperature change

* Corresponding author.
E-mail address: raghavan@iitm.ac.in (V. Raghavan).

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Table 1
Correlations for calculating minimum fluidization velocity.

Investigators	Correlation
Wen and Yu [2]	$\mathrm{Re}_{mf} = \sqrt{33.7^2 + 0.0408\,Ar} - 33.7$
Subramani et al. [4]	$\mathrm{Re}_{mf} = Ar/1502$
Jiliang et al. [6]	$U_{mf} = [0.28\sum_{i=1}^{n} x_i d_i^{0.599}(\rho_s/\rho_g)]/\upsilon^{0.066}$; x_i: mass fraction of particles of size d_i
Grace [7]	$\mathrm{Re}_{mf} = \sqrt{27.2^2 + 0.0408Ar} - 27.2$
Chitester et al. [8]	$\mathrm{Re}_{mf} = \sqrt{28.7^2 + 0.0494Ar} - 28.7$
Nakamura et al. [9]	$\mathrm{Re}_{mf} = \sqrt{33.953^2 + 0.0465Ar} - 33.953$

for Geldart's group B particles. Kunii and Levenspiel [14] summarized the effects of temperature on the bubble size. They reported that, for Geldart A particles, bubble frequency increases and the size of the bubble decreases significantly with an increase in temperature. For Geldart B particles, the bubble size was almost constant and slightly smaller than that at ambient condition. On the other hand, bubble size remained unaffected by the temperature when Group D particles were fluidized.

Numerical studies on fluidized beds operating at elevated temperatures have been primarily aimed at determining the heat transfer characteristics such as heat transfer coefficient, effective thermal conductivity and particle Nusselt number [15,16]. A combined CFD-DEM (Computational Fluid Dynamics-Discrete Element Method) methodology has been used to estimate inter-phase convection, particle wall conduction and particle radiation effects. CFD-DEM method is computationally expensive and cannot be used to model large or real scale reactors. Moreover, determination of heat transfer characteristics is important for reactors having internal components such as heat exchanger tubes and baffles. These internal components are usually located much above the free board where the interaction of particles are less.

Several studies have been reported on lab/pilot scale reactors [17–20] without any internal components. This is particularly true for fluidized bed gasification reactors, where it is uncommon to recover the heat from the main column. The purpose of such investigations has been to improve the fundamental understanding of the flow physics and performance parameters such as conversion efficiencies and product gas composition. Additionally, fluidized beds operating in a reactive environment are generally well insulated and hence, wall-to-bed heat transfer need not be modeled. Accounting for exchange of interphase momentum, heat and mass transfer are important to model such reactive gas-solid flows. Fluidized bed reactors for combustion or gasification of coal or biomass, especially when they reach quasi steady state, operate within a stable temperature range. This temperature becomes primarily responsible for fluidization at a given operating condition. Additionally, the size of the particle may change due to heterogeneous reactions, particle attrition and erosion. Change in the particle size affects U_{mf}, which subsequently alters the bed hydrodynamics. Modification in the bed hydrodynamics can significantly influence the reactor performance as it affects fluidization. Therefore, it is important to understand the hydrodynamics of fluidized bed reactors at elevated temperatures, first in a non-reactive environment. It is evident from literature that the focus of the earlier experimental investigations has been to determine U_{mf} at various temperatures using different particle sizes. Apparently, studies on the effect of reactor temperature on hydrodynamics parameters such as bubble size, particle velocity, and voidage profile are scarce. Experimental determination of such parameters is highly challenging, if not impossible. In such a scenario, numerical simulations can be of immense help. Euler-Euler two fluid methodology (E-E) has been frequently used to model fluidized beds in non-reactive as well as in reactive environments [21–24]. However, there is not much literature on numerical studies on hydrodynamics at elevated temperatures in non-reactive environment using E-E methodology. These points form motivation of this study and the present work aims to investigate the hydrodynamics of gas-solid flows at elevated temperatures using E-E method.

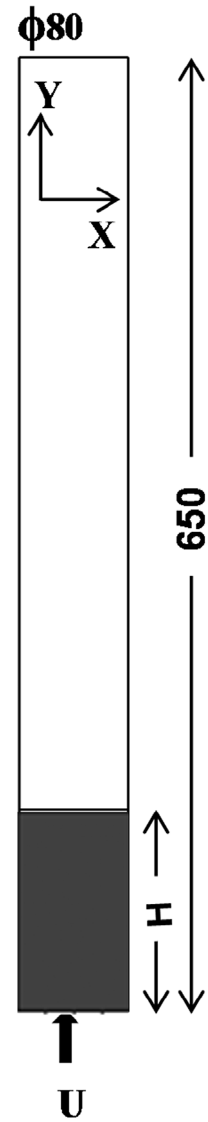

Fig. 1. Computational domain.

2. Numerical model and quantification of discretization errors

Computational domain used in the present simulations corresponds to the experiments of Jiliang et al. [6] and shown in Fig. 1. Although the actual height of the fluidization column used in experiments is 1.3 m, only a height of 0.65 m is considered in the computational domain. This is valid since bubbling characteristics in a slow bubbling regime is studied and expanded bed height is expected to be much lesser than 0.65 m. Three-dimensional model is created and discretized using cells of different sizes based on particle diameter. Quartz sand particles have been used, corresponding to the experimental data of Jiliang et al. [6]. It should be noted that the minimum size of a cell should be larger than the particle diameter, while using two fluid model for simulating particle laden flows. Thus, a different approach is required for quantifications of discretization errors. Hence, in the present study, quantification of errors due to discretization (grid independence study) is performed using the procedure suggested by Celik et al. [25]. In this