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Hydrodynamic characteristics of gas–solid tapered fluidized beds: Experimental studies and empirical models

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ABSTRACT

Understanding the hydrodynamic behavior of tapered fluidized beds is essential for accurate design and better operation in these fluid–solid contactors. Minimum fluidization velocity, minimum velocity of full fluidization, maximum pressure drop and bed expansion ratio are more important hydrodynamic characteristics in tapered fluidized beds. In this study, based on experimental data, dimensional analysis has been used to develop dimensionless correlations for predicting hydrodynamic characteristics of Geldart B particles in tapered fluidized bed. The effects of bed geometry, static bed height, particle density, size, and sphericity and also interparticle forces on hydrodynamic behavior of tapered fluidized beds have been investigated. Numerical comparison indicated that the predictions of the present model are in good agreement with experimental data. The ability of the proposed models to predict hydrodynamic characteristics of fluidized particles has been compared to that of existing models in the literatures.

1. Introduction

Fluidized beds are generally used when a high contact area between solid particles and a fluid phase is required [1]. Some important applications of fluidized bed processes are catalytic reactions [2], waste incineration [3], water treatment [4], drying [5], coating [6], crystallization [7], and granulation [8]. Fluidized beds are typically constructed in cylindrical and tapered geometries. Although the cylindrical form is more commonly used, the tapered form is widely used in the specialized processes in chemical, pharmaceutical, and food industries. Due to conical shape of the tapered beds, the cross section of the bed increases with increasing bed height, and results in a decrease in fluid velocity from the bottom to the top of the bed.

The variable fluid velocity along the bed height, provides unique hydrodynamic characteristics for the tapered fluidized beds in special flow regimes such as non-slugging fluidization [9] and in applications where high heat and mass transfer [10], good mixing, and uniform temperature profile [11] are required. Also, in applications where a wide size distribution of particles exists, tapered beds allow fluidization of coarser particles at the bottom of the bed, while elutriation is avoided at the top of the bed [12].

Design and operating of fluidized beds require an understanding of their hydrodynamics [13]. Minimum fluidization velocity (U_{mf}), minimum velocity of full fluidization (U_{mff}), maximum pressure drop (ΔP_{max}), and bed expansion ratio (R) are among the most important hydrodynamic characteristics which are often considered and investigated for proper operation of fluidized beds [14,15].

The models that are developed in recent years to predict the hydrodynamic parameters of tapered fluidized beds can be categorized into two main groups: the first one is based on the modified Ergun equation [15], while the second relies on empirical equations. The models presented by Peng and Fan [15], Biswal et al. [16], Agrawal and Roy [17], Jing et al. [18], Shan et al. [19], and Kaewklum and Kuprianov [20] are among the first group of models. Although spherical particles were commonly applied in the experimental work that led to these models, different particle types and tapered angles were used.

The second group of models used dimensional analysis to develop empirical correlations to predict hydrodynamic behavior of tapered fluidized beds. Sau et al. [21] conducted experiments using spherical and non-spherical particles of different sizes and tapered angles, to predict U_{mf} and ΔP_{max}. Their proposed model to predict U_{mf}, does not consider the effects of static bed height (H_o) and the inlet bed diameter (D_o), and therefore, it has little ability to predict different bed geometries. Also, their model to predict ΔP_{max} is not accurate, as it does not take into account the tapered angle.

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Table 1
Geometry of Plexiglas beds.

Bottom diameter (D_o) cm	Top diameter (D_1) cm	Bed height (h) cm	Tapered angle (α)°
7	14	26	8
12	24	30	12
15	35	33	17

Khani [22] used dimensional analysis to develop a model for U_{mf}, that included bed inlet diameter for increased model accuracy. To increase the ability of models used for small tapered angles, sin(α) was replaced by cos(α) in the U_{mf} and ΔP_{max} models. However, none of these models include the static particle bed height.

Several researchers have developed models to predict expansion ratio in tapered beds. Biswal et al. [23] measured the expansion ratio of spherical glass particles in a tapered bed with 10° tapered angle at different inlet gas velocities. They used dimensional analysis to propose an equation that predicts expansion ratio of spherical particles. As their experimental data was obtained using only glass spheres in a bed having 10° tapered angle, their model cannot be generalized to other particle shapes and bed angles. Maruyama and Koyanagi [24] studied the hydrodynamic behavior of spherical particles in different tapered beds to develop a mathematical model that predicts bed expansion in slugging flow regime. Depypere et al. [25] studied the fluidization of spherical particles in a tapered bed with 8.13° tapered angle, for developing a model to predict bed expansion ratio by considering the static pressure and the wall temperature.

Sau et al. [26] used the dimensional analysis method to develop correlations to describe bed expansion ratios of both spherical and non-spherical particles in tapered beds, having different angles and geometries. However, the effect of the tapered angle is ignored in their models.

Although several empirical and analytical models have been developed by researchers to predict U_{mf}, U_{mff}, ΔP_{max}, and R in tapered beds, however none of these models include the interparticle forces. Previous studies suggest that the interparticle forces affect the behavior of fluidized particles in fluidized beds [27–29]. The impact of interparticle forces on the hydrodynamic characteristics of particles in fluidized beds can be evaluated using the dimensionless group, called Bond number (Bo) [30,31], which is defined as the ratio of the attractive interparticle forces to the particle weight, and plays an essential role in bulk cohesion.

The main objective of this research is to study the effects of bed tapered angle and static bed height on the hydrodynamic characteristics of particles with different nature, density, size, and sphericity. Hydrodynamic parameters evaluated in this study include minimum fluidization velocity, minimum velocity of full fluidization, maximum pressure drop, and bed expansion ratio. Dimensional analysis is used to develop dimensionless correlations that predict the above hydrodynamic parameters. This study implements the effect of interparticle forces on hydrodynamic parameters by incorporating the Bond number in dimensionless correlations. The ability of the proposed models to predict the hydrodynamic characteristics of fluidized particles was compared to that of existing models in the literatures.

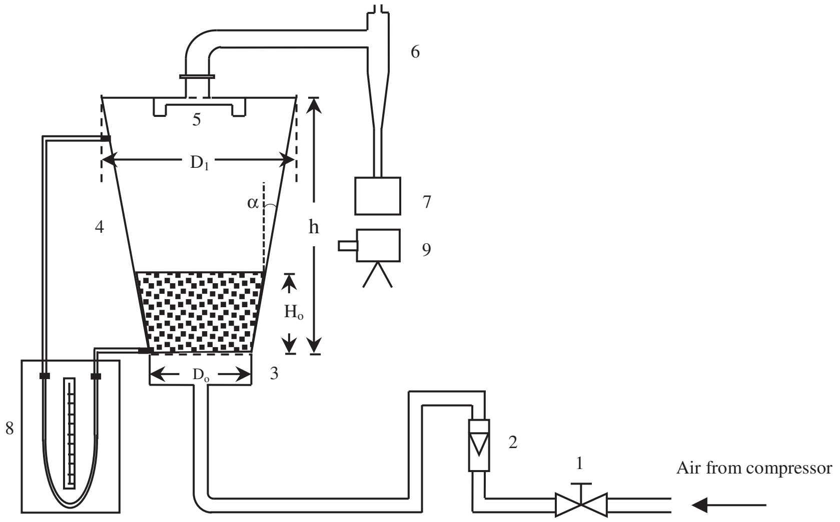
2. Experimental set-up and procedures

2.1. Apparatus

The experiments were accomplished in tapered fluidized beds made of Plexiglas with different geometries as summarized in Table 1. A plate with a standard mesh of 170 was used as the bed material support and distributor at the bottom. A compressor (HSS make, model: MICAS-PH-80-1055) with 300 L/min and 400 L capacity was used to prepare needed air. Two pressure ports, one at the bed inlet (just above the distributor shown in Fig. 1) and the other at the exit section of the bed, were supplied to measure pressure drop along the height of the bed.

A U-tube manometer (1.5 m height and ±2% FSD accuracy) which used colored water as manometric fluid, recorded pressure drop. Ambient air, after passing through a silica gel tower and two rotameters, was used as the fluidizing agent. Two rotameters (accuracy ±2% FSD), one for the lower range (0–5 m^3/h) and the other for the higher range (5–20 m^3/h), were employed to measure the air flow rates. A digital camera (Canon Power Shot SX400 IS) was used to take pictures of flow regime and determine the bed height.

Force spectroscopy analysis was used to measure interparticle forces. The atomic force microscope (AFM, Ara-Research Co., Tehran) provided force–displacement curve for particles.



1-Valve, 2-Rotameter, 3-Distributor plate, 4-Bed, 5-Filter, 6-Cyclone, 7-Receiver, 8-Manometer, 9-Digital camera

Fig. 1. Schematic diagram of the experimental set-up.