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Fluid Dynamics and Transport Phenomena

Hydrodynamics of three-phase fluidization of homogeneous ternary mixture in a conical conduit — Experimental and statistical analysis

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ABSTRACT

Hydrodynamics of conical fluidized bed differ from that of columnar beds by the fact that a velocity gradient exists along the axial direction of the bed. The gas–liquid–solid fluidized bed has emerged in recent years as one of the most promising devices for three-phase operations. Such a device is of considerable industrial importance as evident from its wide applications in chemical, refining, petrochemical, biochemical processing, pharmaceutical and food industries. To explore this, a series of experiments have been carried out for homogeneous well-mixed ternary mixtures of dolomite of varying compositions in a three-phase conical fluidized bed. The hydrodynamic characteristics determined included the bed pressure drop, bed fluctuation and bed expansion ratios. The single and combined effects of operating parameters such as superficial gas velocity, superficial liquid velocity, initial static bed height, average particle size and cone angle on the responses have been analyzed using response surface methodology (RSM). A 2^5 full factorial central composite experimental design has been employed. Analysis of variance (ANOVA) showed a high coefficient of determination value and satisfactory prediction second-order regression models have been derived. Experimental values of bed pressure drop, bed fluctuation and bed expansion ratios have been found to agree well with the developed correlations.

1. Introduction

With the development of fluidized bed coal combustion, the recent interest in the use of fluidized beds for waste utilization and dry solids separation and the potential applications of multi-component fluidized beds is on the rise. It is because of the fact that fluidized particles of uniform in size at the beginning, may change due to attrition, coalescence and chemical reaction, thereby affecting the quality of fluidization by high elutriation loss, de-fluidization, segregation, and inhomogeneous residence time in the bed leading to non-uniform products of wide particle size distribution. Therefore, Sau *et al.* [1] stated that proper characterization of bed dynamics for binary and multi-component mixtures in gas–solid systems is an important prerequisite for their effective utilization, where the combination of particle size, density and shape influences fluidization behavior.

Biswal *et al.* [2–4] developed theoretical models for minimum fluidization velocity and bed pressure drop for spherical particles for gas–solid systems in conical vessels. Due to angled walls, random and unrestricted particle movement occurs in a tapered surface with reduced back mixing. They, therefore, proposed a modified equation for calculation of the maximum pressure drop. Later, Peng and Fan [5] made an in-depth study of hydrodynamic characteristics of solid–liquid fluidization in a tapered bed and derived theoretical models for the prediction of minimum fluidization velocity and maximum pressure drop, based on the dynamic balance of forces exerted on the particle. However, the experiments were carried out for spherical particles only. Jing *et al.* [6] and Shan *et al.* [7] proposed models for ΔP_{mf} and U_{mf} for gas–solid conical fluidized beds for spherical coarse and fine particles based on Peng and Fan [5] models, but neglected pressure drop due to the kinetic change in the bed.

A correlation for fluctuation ratio in conical vessels for regular particle has been developed by Biswal *et al.* [8] using dimensional analysis approach based on four dimensionless groups neglecting the effect of density of gas and solid particles. They have developed a correlation for the bed fluctuation ratio for irregular particles in conical vessel. Singh *et al.* [9] have developed correlations for bed fluctuation ratio for binary homogeneous and heterogeneous mixtures of spherical and non-spherical particles in conical conduits. Singh *et al.* [10,11] have also developed correlations for bed expansion ratio for cylindrical and non-cylindrical beds. Dora *et al.* [12] have studied the bed expansion and fluctuation ratios in a gas–solid conical fluidized bed for homogeneous ternary mixture of irregular particles.

Current literature deals with the development of mathematical models for fluctuation and expansion ratios for ternary mixtures in a conical bed with different cone angles. Practically no work has been carried out for three-phase fluidization in a conical bed. The objective of the

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present work is to study the hydrodynamic characteristics of ternary mixture in a three-phase conical fluidized bed with different cone angles 4.61°, 5.13°, 7.47° and 11.2° (incorporating the similar values of the earlier study [12]) and to develop a mathematical model for the determination of fluctuation and expansion ratios by statistical analysis.

2. Materials and Methods

The experimental set-up consists of a single stage air compressor of sufficient capacity, an accumulator for storage of air at constant pressure 137895Pa (20 pound per square inch, gauge), a water tank and a liquid pump 373W (0.5 HP) as shown in Fig. 1.

Two rotameters, one for water (0–10 L·min^{-1}) and the other for air (0–50 L·min^{-1}) were used to measure the water and air flow rates respectively. A 40 mesh screen at the bottom served as the support as well as the distributor. The inside hollow space of the distributor was filled with glass beads of 1.5 cm outer diameter for uniform water and air distribution. The conical conduits with different cone angles are made up of Perspex sheets to allow visual observation. Detailed dimensions for the conical conduits used are given in Table 1.

Two pressure tapings were provided with for noting the bed pressure drop. A gate valve of 15 mm inner diameter was provided in the line to control the water flow to the bed. Two sets of manometer with carbon tetrachloride (for low pressure range) and mercury (for high pressure range) as manometric liquid were used to record the pressure drop. A high speed digital camera has been used for verification of the maximum and minimum heights of the bed during fluidization.

Three closely-sized samples of dolomite (as shown in Table 2) were used for the investigation. For ternary mixtures, fairly good mixing has been achieved by coning and quartering method as done in experimental practice and classification has been avoided since the ratio of the particle-sizes of two successive fractions in the mixture was kept below 1.3. The scope of the experiments has been presented

Table 1
Dimensions of conical conduits

Dimension	Tapered angle/(°) 4.61	5.13	7.47	9.52	11.2
Bottom diameter/m	0.048	0.050	0.042	0.050	0.045
Top diameter/m	0.132	0.135	0.174	0.212	0.245
Height of the column/m	0.520	0.470	0.504	0.483	0.510

Table 2
Scope of the Experiment

(A) Ternary mixture properties

Materials	Particle size $D_p \times 10^3$/m	Particle size ratio	Mixture	Composition	Avg. particle size $D_p \times 10^3$/m
D_{p1}	1.540	$D_{p1}/D_{p2} = 1.18$	Mixture 1	20:30:50	1.23
			Mixture 2	20:40:40	1.25
D_{p2}	1.303	$D_{p2}/D_{p3} = 1.18$	Mixture 3	20:50:30	1.27
D_{p3}	1.101	$D_{p1}/D_{p3} = 1.40$	Mixture 4	20:60:20	1.30
			Mixture 5	20:70:10	1.32

(B) Bed parameter

H_s/m	0.1	0.125	0.15	0.175	0.2

(C) Cone angle

tanα	4.61	5.13	7.47	9.52	11.2

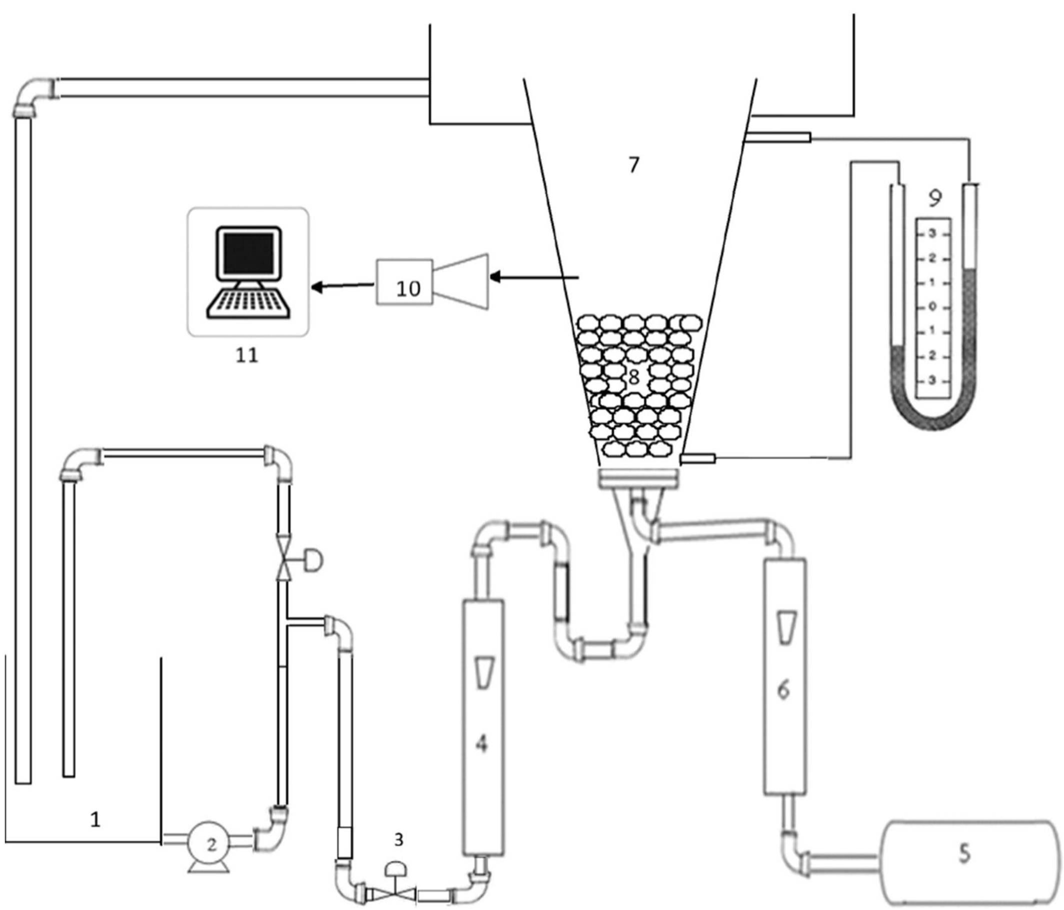

Fig. 1. Schematic diagram of experimental set-up.
1. Water Tank 2. Pump 3. Control valve 4. Water rotameter 5. Compressor 6. Air rotameter 7. Tapared Column 8. Bed material 9. U-tube manometer 10. High speed camera 11. Computer.

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