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Original Research Paper

Expansion behaviour of a binary solid-liquid fluidised bed with different solid mass ratio

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ABSTRACT

This study reports the effect of particle mass compositions on the bed expansion behaviour of a binary solid liquid fluidised bed (SLFB) system. Experiments were performed comprising equal density (2230 kg m^{-3}) spherical glass beads particles of diameter 3, 5 and 8 mm and water as fluidising medium with different particle mass ratios varying from 0.17 to 6.0. In the expanded bed, both segregated and intermixed zones were observed depending on the different particle diameter combinations. In a completely segregated SLFB, the bottom monosized layer exhibited a negative deviation ∼23% whereas a positive deviation ∼25% was found in the top monosized layer when compared with the corresponding pure monosized system. A small mixing zone spanning approximately two particle diameters thick was observed to exist even in a completely segregated SLFB for higher diameter ratio cases. A slight decrease in the mixing zone height was noted with increasing liquid superficial velocity. For lower diameter ratio cases, a relatively lager mixing zone height was observed which increased with increasing liquid superficial velocity. The bed expansion ratio was noted to decrease with increasing solid mass ratio however it increased with increase in the fluidising velocity ratio following a reasonable power law trend. The expanded bed height of the binary mixture was not entirely additive of its corresponding monocomponent bed heights and both positive and negative deviations were observed. Finally, a two-dimensional (2D) Eulerian-Eulerian (E-E) model incorporating the kinetic theory of granular flow (KTGF) was used to quantify the binary system hydrodynamics. The model predicted expanded bed height agreed with experimental measurements within ±6% deviation. Presence of a mixing zone was also confirmed by the CFD model and simulated particle phase volume fraction distribution qualitatively agreed with the experimental visualisations.

1. Introduction

Solid liquid fluidised bed (SLFB) systems are widely used in the chemical, mineral processing, biochemical and food industries involving variety of applications such as water treatment, sedimentation, separation of minerals, ion exchange, adsorption, crystallization, etc., due to efficient contact between the solid and liquid phase [1,2]. Over the last four decades, interactions and motion of phases in SLFBs were studied by many researchers experimentally [1,3–17] as well as numerically [18–34] employing computational fluid dynamics tool to understand the complex hydrodynamics of this system.

The hydrodynamics of solid-liquid fluidised bed is inherently complex due to interactions between the fluid and particle phase, particle-particle phase, and particle-wall. These interactions introduce further complexities when more than one solid phase is present in the system, more specifically when the solid phases differ in diameter and/or density as well as shape. In almost every industrial application, a particle size distribution often exists which indeed raises a requirement to investigate the fluidisation behaviour in the multi-particle system. Simplest of these SLFB systems is the binary particle system where three different characteristics are generally reported e.g. complete segregation (CS), partial segregation (PS) and no segregation (NS). These characteristics

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Nomenclature

C_D	drag coefficient, [–]
$C_{D\infty}$	drag coefficient under terminal rise conditions, [–]
$C_{fr,\ ss}$	coefficient of friction between solids, [–]
C_1, C_2	constant in Eq. (1), [–]
C_3, C_4	constant in Eq. (2), [–]
C_5, C_6	constant in Eq. (6), [–]
d_r	diameter ratio of larger to smaller solids, d_{S2}/d_{S1} [–]
d_S	diameter of solid particle, [m]
D_c	column diameter, [m]
e_{SS}	solid-solid interaction restitution coefficient, [–]
e_{SW}	solid-wall interaction restitution coefficient, [–]
F_{Di}	momentum exchange term, [N]
g	gravitational acceleration, [m s^{-2}]
$g_{0,ss}$	radial distribution function, [–]
h_e	axial bed height, [m]
h_{mix}	intermixed zone height of binary particle, [m]
h_p	packed bed height, [m]
h_r	bed expansion ratio, $(h_e - h_p)/h_p$ [–]
k_L	turbulent kinetic energy, [m^2 s^{-2}]
M_S	solid mass, [g]
M_r	mass ratio of larger to smaller solids, M_{S2}/M_{S1} [–]
n	Richardson-Zaki index, [–]
P	static pressure, [Pa]
P_S	solid pressure, [Pa]
P_{kL}	production of turbulent kinetic energy, [m^2 s^{-3}]
Re_{Si}	solid particle Reynolds number, [–]
$V_{S\infty}$	terminal settling velocity of particle, [m s^{-1}]
V_{mf}	minimum Fluidisation velocity, [m s^{-1}]
V_L	liquid superficial velocity, [m s^{-1}]

Greek letters

β_{SL}	liquid-solid momentum exchange force, [N]
β_{SS}	solid-solid momentum exchange force, [N]
ε	energy dissipation rate per unit mass, [m^2 s^{-3}]
ϵ_L	bed voidage, [–]
ϵ_S	solid volume fraction, [–]
θ	Granular temperature, [m^2 s^{-2}]
λ_S	bulk viscosity of solid, [kg m^{-1} s^{-1}]
μ_L	viscosity of liquid, [kg m^{-1} s^{-1}]
μ_S	solid viscosity, [kg m^{-1} s^{-1}]
μ_T	turbulent viscosity, [kg m^{-1} s^{-1}]
$\mu_{eff,s}$	effective viscosity of solid, [kg m^{-1} s^{-1}]
$\mu_{eff,L}$	effective viscosity of liquid, [kg m^{-1} s^{-1}]
ρ_L	liquid density, [kg m^{-3}]
ρ_S	solid density, [kg m^{-3}]
ρ_{SM}	solid mixture density along the axial direction, [kg m^{-3}]

Subscripts

L	liquid
S	solid
∞	Infinite medium
1	solid particle 1 (smaller)
2	solid particle 2 (larger)

Abbreviations

2D	two dimensional
3D	three dimensional
CS	complete segregation
CFD	computational fluid dynamics
E-E	Eulerian-Eulerian approach
FB	fluidised bed
KTGF	kinetic theory of granular flow
NS	no segregation
NG	not given
PS	partial segregation
SLFB	solid-liquid fluidised bed

apparently depend on the terminal settling velocity of the particles. When a binary mixture is fluidised, solids having higher terminal settling velocity tend to settle at the bottom of the fluidised bed whereas solids with lower terminal settling velocity fill the upper section of the bed with a transition zone in between. The volume fractions of both solid phases change continuously in the transition zone.

A widely used hypothetical notion in binary SLFB systems is that total bed height is additive, i.e. bed height equals to the sum of heights of the two individual component beds fluidised at the same liquid superficial velocity [11,35–39]. However, a significant negative deviation was reported in another study [4]. Consequently, the hypothesis that combined bed heights are additive requires further investigation. The literature review presented in Section 2 indicates that segregation hydrodynamics in binary SLFB system such as complete segregation, partial segregation and no segregation mainly occur due to both unequal diameter and density ratio. While the effect of unequal density for the observed segregation behaviour is more intuitive, effect of particle diameter ratio for a constant particle density system needs further attention. Literature review indicates that individual solid mass for the binary SLFB was not reported in most of the cases which is a critical requirement for any modelling study in this area to satisfy the solid phase mass conservation in the system. Consequently, the effect of solid mass ratio on the bed expansion behaviour for constant particle density system remains rather unexplored. It is also of interest to understand the dynamics in the mixing zone specifically the effect of superficial velocity and mass ratio which provides an insight to the dispersion behaviour in SLFB system. It is also noted that this aspect has not been addressed even in the previously reported CFD modelling studies in this area. In line with these knowledge gaps, the specific aims of this paper were to quantify the followings using a combination of experimental and numerical modelling approach:

(a) bed expansion behaviour for the mono and binary components SLFB under similar operating conditions and effect of solid loading patterns on the final bed expansion behaviour.
(b) effect of different solid mass ratios on the bed hydrodynamics.
(c) effect of liquid superficial velocity on the bed expansion for different solid mass loadings.
(d) bed expansion behaviour and spatial distribution of individual phase volume fraction at different superficial velocity using a CFD model.

2. Previous work

Kennedy and Bretton [15] studied dispersion behaviour of the binary solid spheres in a liquid fluidised bed and observed no segregation behaviour in a narrow solid diameter ratio range ($d_r \sim 1.01$–1.1) for uniform density system ($\rho_r = 1.0$). The observed