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Hydrodynamics of a gas–solid fluidized bed with thermally induced interparticle forces

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HIGHLIGHTS

- The effect of interparticle forces on hydrodynamics of gas–solid fluidized bed is studied.
- The fluidization characteristics of the bed can be greatly influenced by interparticle forces.
- The minimum fluidization velocity increases with interparticle forces.
- The gas is more prone to pass through the bed in the emulsion phase when interparticle forces increase.
- Enhancing interparticle forces will increase the bubbling to turbulent regime transition velocity.

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ABSTRACT

In this study, a polymer coating approach was applied to increase and adjust the level of cohesive interparticle forces (IPFs) in a gas–solid fluidized bed. This novel approach is based on coating spherical inert particles with a polymer material having a low glass transition temperature followed by using the coated particles in a gas–solid fluidized bed. Since the level of artificial IPFs inside the bed depends on the temperature of the coated particles, it was simply controlled by the temperature of the inlet air. Accordingly, the system temperature was gradually varied near and slightly above the glass transition temperature of the polymer, between 20 and 40 °C, to investigate the influence of IPFs on the fluidization behavior of the bed at different superficial gas velocities, covering fixed bed state, bubbling, and turbulent fluidization regimes. The study of hydrodynamics was carried out through the visual observation of bed height, the measurement of bed pressure drop, and the recording pressure signals in the windbox and dense bed. Experimental results indicated that enhancing the level of IPFs in the bed can alter the fluidization behavior of the bed from Geldart (Geldart, 1973) group B behavior to Geldart group A and even Geldart group C behaviors, result in a fixed bed with a looser structure that can hold more gas inside, increase the characteristic fluidization velocities, such as minimum fluidization velocity and transition velocity from a bubbling to turbulent fluidization regime, increase the tendency of the fluidizing gas passing through the emulsion phase in the bubbling regime, and result in a noticeably larger bubble size at gas velocities slightly higher than the bubbling to turbulent transition velocity of the bed without IPFs.

1. Introduction

Together with the basic physical properties of powder, such as particle density, size, shape and roughness, interparticle forces (IPFs) are among the most important parameters affecting the fluidization behavior of particulate materials. In regard to the significance of IPFs, it has been well demonstrated that the flow dynamics of Geldart [1] group C powders is mainly governed by IPFs [2]. This results in completely different behavior compared to the other groups of Geldart classification with low or no IPFs. In addition, research studies on the subject of the hydrodynamics of a gas–solid fluidized bed at high temperatures clearly pointed out that some peculiar phenomena, which happen at elevated temperatures, cannot be solely explained in light of the influence of this variable on the properties of the fluidizing gas [3–11]. In fact, it turns out to be obvious that the simultaneous influence of the operating temperature both on the gas phase and the solid phase, considered as variations in IPFs, must be taken into account to describe these behaviors well. Therefore, it is highly necessary to clearly address how IPFs can change the fluidization dynamics of a gas–solid fluidized bed.

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Nomenclature

Acronyms

ABF	Agglomerate Bubbling Fluidization
APF	Agglomerate Particulate Fluidization
COP	coherent component
CSB20	coated sugar beads at 20 °C
CSB30	coated sugar beads at 30 °C
CSB40	coated sugar beads at 40 °C
Ga	Geldart Number
HDFs	hydrodynamic forces
IOP	incoherent component
IPFs	interparticle forces
PEA	Poly Ethyl Acrylate
PMMA	Poly Methyl MethAcrylate
PSD	power spectral density
SB20	fresh sugar beads at 20 °C

Symbols

a	constant in Eq. (20) (sec^{-b})
A	cross-sectional area of the fluidizing column (m^2)
b	constant in Eq. (20) (−)
D	column diameter (m)
d_p	mean particle diameter (μm)
D_b	bubble diameter (m)
f	frequency (Hz)
f_e	emulsion phase fraction (−)
h	bed height (m)
h_{mf}	bed height at minimum fluidization state (m)
j	complex number (−)
K	number of segments (−)
M_s	number of data points in each segment (−)
N	number of data points (−)
p_i	pressure signal (Pa)
p_x	pressure signals recorded in the windbox (Pa)
p_y	in-bed gauge pressure signals (Pa)
$\bar{p}$	mean value of the pressure signals (Pa)
P_{xx}	average power spectral density of gauge pressure signals recorded in the windbox (Pa^2/Hz)
P^i_{xx}	power spectral density of each segment (Pa^2/Hz)
P_{xy}	cross power spectral density of gauge pressure signals recorded in the windbox and in the dense bed (Pa^2/Hz)
P^*_{xy}	conjugate of P_{xy} (Pa^2/Hz)
P_{yy}	average power spectral density of in-bed gauge pressure signals (Pa^2/Hz)
t_c	contact time (s)
t_D	reptation time (s)
U_B	bubble rise velocity (m/s)
U_c	transition velocity from bubbling to turbulent regime (m/s)
$U_{c,CSB40}$	transition velocity from bubbling to turbulent regime for CSB40 (m/s)
$U_{c,NoIPFs}$	transition velocity from bubbling to turbulent regime for a bed without IPFs (m/s)
$U_{c,SB20}$	transition velocity from bubbling to turbulent regime for SB20 (m/s)
U_g	superficial gas velocity (m/s)
U_{mb}	minimum bubbling velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
$U_{mf,NoIPFs}$	minimum fluidization velocity for a bed without IPFs (m/s)
$U_{mf,SB20}$	minimum fluidization velocity for SB20 (m/s)
U_{tr}	transport velocity (m/s)
V_d	debonding velocity (m/s)
V^*_B	bubble flow rate (m^3/s)
V^*_e	volumetric flow rate of gas flowing through the emulsion phase (m^3/s)
w	window function (−)
W	effective adhesion energy (J)
W_r	maximum adhesion energy (J)

Greek letters

ε	bed voidage (−)
ε_d	emulsion phase voidage (−)
ε_{mf}	minimum fluidization voidage (−)
$\mathcal{K}$	coordination number (−)
μ_g	gas viscosity (Pa.s)
ρ_{ab}	aerated bulk density (kg/m^3)
ρ_p	particle density (kg/m^3)
ρ_{tb}	tapped bulk density (kg/m^3)
σ	standard deviation of pressure signals (Pa)
$\sigma_{xy,i}$	standard deviation of IOP (Pa)
χ	permeability of the packed bed ($m^2(Pa.s)^{-1}$)
ΔP	bed pressure drop (Pa)
ΣV_B	total bubble volume within the bed (m^3)
ΣV_e	total volume of particles forming the bed (m^3)
Υ^2_{xy}	coherence function (−)
$\overline{\Upsilon^2_{xy}}$	average coherence function (−)

Different approaches have been used by researchers to investigate the influence of IPFs on the fluidization behavior of gas–solid fluidized beds. However, easy and accurate control of the level of IPFs that are uniformly distributed throughout the particulate media is the most important criterion for the selection of a method by which IPFs are introduced into a bed of powders. Also, to tackle what was found at high temperatures, the methodology can be chosen to imitate the cohesive behavior found at extreme operating temperatures in a friendlier environment. Techniques that have been applied include the following: increasing the level of van der Waals forces by reducing the mean particle size [12–16]; intensifying the amount of capillary force by the addition of a cohesive agent into the bed [17,18]; application of a magnetic field around the bed [19–21]; and increasing the bed temperature to a high value while cured particles, doped silica catalysts and Ballotini particles with the potassium acetate, were used as bed materials [10,11].

Each of these approaches has specific difficulties in practice. Basically, the magnitude of van der Waals interparticle forces becomes considerably small compared to the hydrodynamic forces (HDFs) for particles in excess of 100 μm in size [22,23]. Accordingly, in order to use van der Waals forces to study the behavior of the bed in the presence of IPFs, it is required to utilize particles smaller than 100 μm in size. For larger particles for which HDFs are dominant, IPFs can be introduced by the addition of a cohesive agent into the bed. However, it is challenging with this approach to have uniform distribution of the liquid phase throughout the particulate bed [24,25]. This results in interparticle force anisotropy inside the bed. Additionally, the application of this technique limits the fluidization study at only low superficial gas velocities. In the third technique, the ferromagnetic particles repel each other when they are perpendicular to the magnetic field and attract each other when they are parallel. This results in mal-distribution of IPFs around the particles, thus, yielding anisotropic attraction/