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Influence of interparticle forces on solids motion in a bubbling gas-solid fluidized bed

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ABSTRACT

This article presents some observations of the effect of interparticle forces (IPFs) on solids motion in a gas-solid fluidized bed operated in the bubbling fluidization regime and at atmospheric pressure. The radioactive particle tracking (RPT) technique was adopted to observe the solids flow pattern and quantify spherical equivalent bubble size, distributions of upward and downward-moving clusters and idle and bubble-induced times, cycle frequency, and axial/radial solids diffusivities. The level of cohesive IPFs was increased and controlled in the fluidized bed with a polymer coating approach. Experimental results showed that the presence of IPFs could effectively modify the solids flow pattern in a bubbling gas-solid fluidized bed. The influence was more pronounced at low gas velocity, where the ratio of the magnitude of IPFs to hydrodynamic forces was high. At constant superficial gas velocity, beds with IPFs contained smaller bubbles indicating a higher tendency of gas entering the dense phase compared to the bubble phase. The different characteristic parameters of solids mixing showed that the favorable effect of IPFs on the division of the fluidizing gas between the bubble and dense phases was accompanied by reductions in the quality of global and local solids mixing.

1. Introduction

Bubbling gas-solid fluidized beds are extensively employed for several chemical processes due to their unique operational advantages, such as intense solids mixing, good gas-solids contact, fuel flexibility, as well as efficient heat transfer [1,2]. These attractive features are driven by the bubble-induced solids circulation within the bed [2,3]. Solids are carried up to the bed surface in the wake of bubbles, or gas voids, and in the drifts formed behind the bubbles [4]. A down flow of solids through the dense phase is present to keep the bed continuity. These sequences yield an axial circulation of solids in the bed, called gross circulation of solids. Simultaneously, a lateral mixing of solids occurs either in the bed, i.e., within the bubble wake and between the wake and the dense phase, or at the bed surface. The former is caused by the lateral movement of bubbles due to interaction and coalescence with neighboring bubbles while the latter is the result of the eruption of bubbles [5–7].

Solids motion directly affects heat and mass transfer rates and, in turn, the overall reaction rate in fluidized bed reactors [5]. Thus, it plays a crucial role in controlling product quality and productivity in such devices [3]. Solids motion can be influenced by numerous parameters, such as bubble size and rise velocity, particle size and density, interaction between gas and solids and between gas/suspended solids and the column wall, bed geometry, and the ratio of bed height to column diameter [1,7–9]. In addition, interparticle forces (IPFs) can alter the bed hydrodynamics [10–12]. Changes in the cohesive flow behavior of powders that are observed at elevated temperatures in many industrial processes, such as drying pharmaceutical granules, curing ceramics, and the combustion of solid fuels [13,14] confirm the importance of this factor. Also, hydrodynamic observations at elevated pressures and/or temperatures demonstrated that the sole consideration of a modification in gas properties resulting from a variation in operating conditions cannot adequately predict fluidization behavior under extreme conditions [12, 15–21]. Accordingly, any attempt to better understand the fluidization characteristics, in particular solids motion, in the presence of IPFs, which would yield a more precise design of fluidized beds, is of great interest.

It has been demonstrated in earlier studies of the group [10,11,22, 23] that the polymer coating approach [22] is a superior technique to introduce and control the level of IPFs in a gas-solid fluidized bed. Spherical inert powders are primarily coated with a polymer material having a low glass transition temperature (9 °C) and are subsequently adopted in a fluidized bed for hydrodynamic study at different levels of cohesive IPFs in this methodology. The degree of IPFs is controlled by the thickness of the coating and system temperature.

The complex solids motion in bubbling fluidized beds poses a significant challenge and a technological risk to plant designers and investors. Despite the fact that many industrial bubbling fluidized bed reactors are operating under conditions where a discernible magnitude of IPFs is

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Nomenclature

Acronyms

Ar	Archimedes number
CSB40	coated sugar beads at 40 °C
HDFs	hydrodynamic forces
IPFs	interparticle forces
PEA	poly ethyl acrylate
PMMA	poly methyl methacrylate
RPT	radioactive particle tracking
SB20	fresh sugar beads at 20 °C

Symbols

A	single particle (−)
C_{iA}	concentration of an agglomerate consisting of i single particles in the bed (1/kg)
d_p	mean particle size (μm)
d_B	spherical equivalent diameter of bubble (m)
D_c	column diameter (m)
D_r	radial diffusivity (m^2/s)
D_z	axial diffusivity (m^2/s)
$D_{z,0}$	axial diffusivity at zero velocity gradient (m^2/s)
g	gravitational acceleration (m/s^2)
h	bed height (m)
K_i	agglomeration rate constant corresponding to r_i (kg/s)
r	radial coordinate (m)
r_i	rate of formation of an agglomerate consisting of $(i+1)$ single particles (1/(kg.s))
t	reaction time (s)
U_g	superficial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
U_W	solids velocity in bubble wake (m/s)
U_z	vertical particle velocity (m/s)
$U_g - U_{mf}$	excess gas velocity (m/s)
z	axial coordinate (m)

Greek letters

α	constant in Eq. 2 (m^2)
γ_z	axial velocity gradient, $[dU_z/dr]$ (s^{-1})
ρ_p	particle density (kg/m^3)

present, surprisingly little has been reported in the literature on the detailed influence of IPFs on the solids motion in these beds. Accordingly, this study is aimed at deploying the time-position data obtained by the nonintrusive radioactive particle tracking (RPT) technique to explore the movement of solids in bubbling gas-solid fluidized beds with different levels of IPFs. The polymer coating approach was exploited in this work to increase the level of cohesive IPFs in the bed.

2. Experimental

The experimental campaign was divided into two parts. The first part was aimed at the preparation of base particles uniformly coated with a thin layer of PMMA/PEA (poly methyl methacrylate/poly ethyl acrylate). The second part focused on the application of powders with different cohesive properties in a gas-solid fluidized bed for hydrodynamic study.

Spherical sugar beads, which accept the PMMA/PEA coating, were selected as the inert base powders. The mean particle size d_p and the particle density ρ_p were 580 μm and 1556 kg/m^3, respectively. These particles belong to group B powders of the Geldart classification [24] at ambient conditions. The coated sugar beads were produced through an atomization process in a spheronizer machine. The thickness of the uniform coating layer was approximately 5 μm at the end of the coating process. Differences in the particle size and density of the fresh and coated sugar beads were only about 1% for both parameters. This means that both powders held similar fluidization characteristics from Geldart classification's point of view. Details of the coating process and its operating conditions are described elsewhere [11,22,23].

The experimental set-up utilized for the fluidization study consisted of a RPT system and an atmospheric pressure gas-solid fluidized bed, built as a Plexiglas cylindrical column with an inner diameter equal to 15.2 cm and 3.0 m in height. Air, adopted as the fluidizing gas, entered the bed through a perforated distributor plate made from aluminum with 157 holes 1 mm in diameter arranged in a 1 cm triangular pitch. Upon demand, air was heated to the desired temperature with the help of an electrical heater located before the windbox. The RPT system included 12 NaI scintillation detectors, which were distributed on three principle planes having four detectors with a 90° spatial angle between two neighboring detectors in each plane. The planes were configured approximately 10 cm apart to entirely cover an axial position of 0–35 cm in height from the distributor plate. The adjacent planes were staggered 45° to keep the farthest distance between detectors on alternate planes [25].

According to earlier studies of the group [10,11,22,23] the highest level of IPFs was observed for the coated sugar beads at 40 °C. Therefore, in order to investigate the influence of IPFs on solids motion in a bubbling gas-solid fluidized bed, fresh sugar beads at 20 °C (SB20), a system without IPFs, and coated sugar beads at 40 °C (CSB40) were selected. The RPT experiments were carried out at low and moderate superficial gas velocities, U_g = 0.30, 0.50 m/s, in the bubbling regime for each system. For all experiments the same amount of particulate material, 3.0 kg, was introduced into the column. It yielded an initial bed height of approximately 20.5 cm ($h/D_c \approx$ 1.35) at ambient conditions (h is the bed height and D_c is the column diameter). The minimum fluidization velocity U_{mf} was experimentally determined by the measurement of bed pressure drop profile. They were 0.16 m/s and 0.25 m/s for SB20 and CSB40, respectively.

To reflect the dynamic fluidization behavior, a radioactive particle tracer was fabricated from a mixture of scandium oxide and epoxy glue mimicking the size and density of the bed material. The radioactive tracer was subsequently activated to 60 μCi. The long half-life of the produced isotope 46Sc allowed the experiment to be run for a long period. The gamma-rays emitted by the tracer were counted by detectors and recorded by a high speed data acquisition system. These counts were analyzed later to calculate the coordinates of the tracer. Details of the RPT experiments and inverse reconstruction strategy for determining the tracer position are described elsewhere [26–28]. In each experiment, the position of the tracer was monitored every 10 ms for 4 h.

3. Results and discussion

3.1. Solids flow pattern and bubble size

Fig. 1 presents solids flow patterns for SB20 and CSB40 at the tested superficial gas velocities. The mean particle flow was predominantly upward at the center of the bed followed by a continuous down flow of solids near the wall for SB20 at U_g = 0.30, 0.50 m/s and CSB40 at U_g = 0.50 m/s. It reveals that solids, in these cases, smoothly ascended with the rising bubbles in the bed center from the bottom layer to the splash zone, where they exhibited a fast horizontal displacement from the center to the wall. They subsequently moved downward along the annulus to keep the bed continuity. However, CSB40 represented a complex solids flow pattern with four active circulation cells within the whole bed at U_g = 0.30 m/s. Under this condition, the dominant pattern was a down flow of solids at the bed center, which deflected the upward solids movement/bubbles toward the wall at regions close to the air distributor. At an intermediate height of the bed, the upward travelling particles encountered the solids flow returning from the top section