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Similarities between gas-solid fluidization in the presence of interparticle forces at high temperature and induced by a polymer coating approach

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ABSTRACT

This study focuses on the hydrodynamic similarities of gas-solid fluidized beds influenced by the presence of interparticle forces (IPFs) at high temperature and induced by a polymer coating approach at near-ambient conditions. The level of IPFs was controlled through the formation of eutectics on the surface of base particles at high temperature. It was adjusted by the temperature of the inlet gas when adopting particles, coated with a thin layer of polymer having a low glass transition temperature, in a gas-solid fluidized bed in the case of polymer coating approach. Similarities were present between the results of the two parts of the study, i.e., in both cases, the minimum fluidization velocity and the bubble size growth rate with the superficial gas velocity in the bubbling regime increased with IPFs while the frequency of macro-structures and the average in-bed differential pressure drop in the bubbling regime decreased with IPFs. The polymer coating approach is therefore capable of simulating most of the conditions of a high temperature fluidized bed operated under the influence of IPFs at near-ambient conditions.

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1. Introduction

The hydrodynamics of gas-solid fluidized beds at elevated temperatures is a critical factor in their design and operation [1]. Nevertheless, the present understanding is far from satisfactory due to the lack of insight about the relative importance of interparticle forces (IPFs) and hydrodynamic forces (HDFs). Owing to the global trend of processing lower quality feedstock in high temperature gas-solid fluidized beds, which can result in the accumulation of low melting point eutectics in the bed, focusing on the evolution of IPFs at elevated temperatures is essential. It draws a lot more attention when hydrodynamic models that are developed based on the experimental data at ambient conditions cannot adequately predict the bed behavior at high temperature when HDFs, i.e., gas properties, are adjusted for the operating conditions. This is due to overlooking possible modifications that can be induced by temperature to the structure of fluidized particles, i.e., the level of IPFs, and, hence, to the flow dynamics of the bed.

The harsh experimental conditions at elevated temperatures only allow for the application of a limited number of measurement techniques for the purpose of hydrodynamic study [2]. Thus, even if all the difficulties associated with the high temperature operation of laboratory and pilot scale fluidized beds are endured, many detailed hydrodynamic characteristics of the bed remain unexplored. However, a polymer coating approach [3,4] can be adopted to reproduce the conditions of a high temperature gas-solid fluidized bed at near-ambient conditions. This technique employs inert base particles coated with a polymer having a low glass transition temperature. With this method, varying degrees of IPFs can be deliberately and accurately adjusted in the bed of coated particles through controlling the inlet gas temperature.

This study aimed to explore the capability of the polymer coating approach in highlighting the influence of IPFs on the bed behavior in a much friendlier environment compared to a high temperature fluidized bed. This was accomplished through comparing the global hydrodynamic characteristics of gas-solid fluidized beds influenced by the presence of IPFs at high temperature and induced by a polymer coating approach at near-ambient conditions. The increase in the level of cohesive IPFs at high temperature was achieved through the formation of eutectics on the surface of base particles.

2. Experimental

High temperature experiments were conducted in an atmospheric pressure pilot scale fluidized bed with a fluidizing section of 20 cm I.D. and 97 cm in height, which was capable of withstanding temperatures up to 1050 °C. Dried and filtered air, as fluidizing gas, was injected into the column through a bubble cap distributor plate with 9 caps each having 4 holes of 6.36 mm on its perimeter. Coarse silica sand (d_p = 820 μm, ρ_p = 2650 kg/m3, U_{mf} at ambient conditions = 0.42 m/s; d_p is the mean particle size, ρ_p is the particle density, and U_{mf} is the minimum fluidization velocity) and olivine

particles (d_p = 565 μm, ρ_p = 3287 kg/m3, U_{mf} at ambient conditions = 0.27 m/s) were employed as the bed materials for this part of the study. According to Geldart's classification [5], these powders are classified as similar to the boundary of group B/group D particles at ambient conditions. A bed inventory of 26.0 kg of silica sand and 31.2 kg of olivine was separately introduced into the bed for the fluidization tests. These inventories resulted a static bed height of approximately 55 cm for each case after accounting for the dead zones (side ports) of the unit. The hydrodynamic tests were attempted in the range of operating temperatures 700-1000 °C and superficial gas velocities 0.60–1.50 m/s. For the sake of brevity, the experimental results obtained at and around 1000 °C will be presented here as similar trends were recognized at other operating temperatures.

Since the sintering temperatures of selected bed materials were well above 1000 °C [6], it can be anticipated that the fluidization behavior of fresh coarse silica sand and olivine powders will be minimally influenced by IPFs up to 1000 °C. In order to increase the level of IPFs in a bed of otherwise fresh silica sand and olivine particles, pre-processed solid fuels, i.e., alkali/alkali earth metal laden coal, were combusted in the bed at 800, 900, and 1000 °C for 1 h each before commencing the hydrodynamic tests. This allowed eutectics to form on the surface of base particles at elevated temperatures. The superficial gas velocity U_g was kept at 1.0 m/s during either the solid fuel combustion at a specific operating temperature or the bed heating toward a higher temperature with the help of propane combustion in the bed. Multiple OMEGA type K thermocouples were located along the axis, from the windbox to the expansion zone of the unit, to monitor the unit temperature. This provided rapid feedback on energy related events and information about the effect of IPFs on the degree of solids mixing in a high temperature fluidized bed [7]. Temperature signals were continuously logged at a sampling frequency of 1 Hz throughout the whole test. A gauge (OMEGA, PX309-002G5V, 0–2 Psig) and a differential (JUMO, 404,304/000-414-415-28-298, 0–100 mbar) pressure transducer were adopted to provide additional insights into the influence of IPFs on the bed hydrodynamics at elevated temperatures. Gauge and differential pressure probes were installed at 30 cm and 15–45 cm above the distributor plate flush to the wall of the unit, respectively. Upon completion of the last solid combustion step at 1000 °C, if the bed remained fluidized, pressure signals were registered at different superficial gas velocities, each for 4 min at a sampling frequency of 400 Hz. The bed temperature was adjusted by the combustion of propane in the bed under this condition.

In order to investigate the influence of IPFs on fluidization behavior using the polymer coating approach, coarse sugar beads (d_p = 580 μm, ρ_p = 1556 kg/m3, U_{mf} at ambient conditions = 0.18 m/s), which belong to Geldart group B powders at ambient conditions, were primarily coated with a thin polymer layer, i.e., approximately 5 μm, of PMMA/PEA (Poly Methyl MethAcrylate/Poly Ethyl Acrylate). This was accomplished through an atomization process in a spheronizer machine. More details about the coating procedure and its operating conditions can be obtained elsewhere [3,4,8].

All experiments dealing with the polymer coating approach were conducted in a cold atmospheric pressure gas-solid fluidized bed, which was constructed with a Plexiglas column 15.2 cm I.D. and 3.0 m in height. Dried and filtered air, as the fluidizing gas, was introduced into the bed through a perforated distributor plate that contained 157 holes 1 mm in diameter arranged in a 1 cm triangular pitch. The fluidizing air passed through an electrical heater before entering the column to adjust its temperature to the desired process set-point. Uncoated/fresh and coated sugar beads were used separately in the fluidized bed. The fresh sugar beads at 20 °C, SB20, served as a reference system with a minimum level of IPFs and coated sugar beads at 30 and 40 °C, CSB30 and CSB40, respectively, represented systems being influenced by the presence of IPFs. The impact of IPFs on the bed hydrodynamics was higher for CSB40. A bed inventory of 4.0 kg of either fresh or coated sugar beads was fed into the column, which resulted in a fixed bed

height of approximately 26 cm at ambient conditions. For each system tested, the hydrodynamic tests were carried out at different superficial gas velocities (up to 1.3 m/s), covering the fixed bed state and bubbling and turbulent fluidization regimes. This was achieved through recording different pressure signals from the bed at a sampling frequency of 400 Hz for a period of 4 min at each superficial gas velocity. A differential pressure transducer (MODUS, R32–100, 0–100 in water) approximately measured the total bed pressure drop (0.95–200 cm above the distributor plate). A gauge (OMEGA, PX309-002GI, 0–2 Psig at 17.5 cm above the distributor plate) and a differential (OMEGA, PX272-20DI, 0–20 in water at 10–25 cm above the distributor plate) pressure transducer were employed to record in-bed pressure signals.

3. Results and discussions

3.1. Effect of IPFs on U_{mf}

The bed temperature measurement was adopted as the first indication to highlight changes in the fluidization behavior of spent particles, i.e., particles with IPFs after steps of solids fuel combustion, at elevated temperatures. This approach was followed since increasing the level of IPFs decreases the quality of solids mixing in a gas-solid fluidized bed [9] and the degree of bed temperature profile uniformity reveals the extent of solids mixing within the bed [7]. In order to investigate the effect of IPFs on U_{mf} at high temperature through the temperature measurements, an optimized combination of bed material and solid fuel had to be selected to defluidize the bed either in the heat-up pass with propane or the solid fuel combustion. When SiO_2 in the bed material comes into contact with alkali metals (like Na) at elevated temperatures, it can result in the formation of eutectic compounds, like $Na_2O \cdot SiO_2$ with a melting temperature of 874 °C [10,11]. Thus, since the fresh silica sand particles consisted mainly of SiO_2 (99.7%wt) in comparison with the fresh olivine particles, which consisted mainly of MgO, SiO_2, and Fe_2O_3 (49.7, 41.5, and 7.3%wt, respectively), silica sand was selected as the bed material for this part of the study. It assisted in reaching a defluidized state with a solid fuel containing a lower amount of alkali metals.

Fig. 1 shows the axial temperature distribution for a bed of spent silica sand particles with a high level of IPFs, which was achieved after the combustion of a solid fuel with a high alkali metal content at 800 and 900 °C, for 1 h each. The uniformity of the temperature profile during solid fuel combustion at 900 °C and heating step to 1000 °C illustrates that the bed was fluidized under these conditions. The discontinuity of temperature readings at different levels at the beginning of solid fuel combustion at 1000 °C, however, shows that HDFs resulting from U_g = 1.0 m/s at 1000 °C were not enough to dominate the high level of IPFs that was present in the bed and keep it fluidized. Hence, the bed became defluidized. Immediately after the defluidization incident, the bed was retrieved and kept adequately fluidized at 1000 °C and U_g = 1.20 m/s. Further manipulations in U_g revealed that the bed could not remain fluidized at superficial gas velocities below 1.10 m/s at 1000 °C. In contrast, a bed of fresh coarse silica sand particles could easily remain fluidized at U_g as low as 0.80 m/s at this operating temperature. It can be inferred from this observation that U_{mf} for a given powder increases with IPFs.

The conventional method of total bed pressure drop variation as a function of U_g in the packed bed state and bubbling fluidization regime was employed to highlight the influence of IPFs on U_{mf} when the level of IPFs was increased by the polymer coating approach. The evolutions of average total bed pressure drop ΔP_{bed} with U_g for beds with different levels of IPFs during increasing and decreasing velocity passes are presented in Fig. 2. Scrutinizing Fig. 2 leads to the same conclusion as made in Fig. 1, i.e., U_{mf} for a given powder increases with IPFs. An identical trend in the variation of U_{mf} with IPFs was also reported by Seville and Clift [12] when the level of IPFs increased by increasing the loading of a nonvolatile liquid on the particles, Gluckman et al. [13] and Compo