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The effect of biomass particles on the gas distribution and dilute phase characteristics of sand–biomass mixtures fluidized in the bubbling regime

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HIGHLIGHTS

- The impact of biomass load on the characteristics of fluidization is demonstrated.
- The effect of biomass load on the gas distribution in a fluidized bed is studied.
- Characteristics of bubble phase in a sand–biomass fluidized bed are investigated.
- The extent of bed expansion and mixing phenomena are scrutinized in bubbling regime.

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ABSTRACT

The gas distribution between the dilute (bubble) and dense (emulsion) phases of a fluidized bed is studied locally and globally in the bubbling regime for mixtures composed of sand and different weight fractions of biomass (2–16%). The dilute phase has been characterized by analyzing the pressure and voidage signals. A suite of pressure transducers was used to measure pressure fluctuations at different locations along the bed. A reflective optical probe measured local voidage signals and was placed at different radii ($0 < r/R < 0.87$) at a height of $h = 175$ mm above the distributor plate. The mean voidage of the bed is increased with higher biomass loading, primarily because of dilution of the emulsion phase. Changing the quantity of biomass in the bed does not significantly affect the voidage of the bubble and emulsion phases. The void (bubble) fraction increases at the center of the bed, whereas it decreases and then increases at the wall region with increasing weight fraction of biomass. Higher quantities of biomass reduce the mean bubble size and boost the bubble frequency at the center of the bed. The core-annulus structure of the bed is intensified for mixtures with relatively low quantities of biomass, while increasing the biomass load leads to a more uniform distribution of small bubbles across the bed improving the fluidization quality.

1. Introduction

Use of biomass has the very important benefits of contribution to the security of fuel supply, lower greenhouse gas emissions, and support for agriculture (Lior, 2010). It is presently estimated to contribute ~10–14% of the world's energy supply (Cui and Grace, 2007).

Thermo-chemical processes, such as combustion, pyrolysis or gasification, are currently the most widespread techniques for producing energy or value-added products from biomass. Fluidized bed reactors are often the best systems for carrying out these processes since they offer multiple advantages over other types of reactors. These advantages include: the ability to handle a variety of fuels with different physical properties, effective gas–solid contact and heat transfer, and economic operation at relatively small scales. However, fluidization of large and light objects, such as biomass particles, is a cumbersome task, which only becomes feasible by mixing a small amount of biomass within a bed composed of conventional fluidization materials, such as sand. The mass content of fuel, e.g., coal or biomass, as a percentage of the total bed mass in bubbling bed combustion or gasification conditions is typically about 1–5%, depending on the fuel type, size and reactivity. Accordingly, it is usually envisaged that one fuel particle is surrounded by many particles of fluidization medium and the effect of biomass content on the bed properties is ignored. However, several multiphase flow complexities arise in practice

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when fluidizing mixtures composed of dissimilar materials. These complexities cannot be estimated by the hydrodynamic behavior of constitutive substances when being fluidized distinctly (Cui and Grace, 2007). Segregation of biomass particles, which tend to migrate to the top of the bed, is one of the most adverse phenomena giving rise to the ineffective heat transfer along the bed, release of volatiles into the freeboard, and deterioration of the activity of the tar decomposition reaction (Shen et al., 2007). Misdistribution of fuel particles along the bed can also bring about very heterogeneous distribution of the gas reactants and products. For instance, non-uniform distribution of oxygen across the bed influences the combustion of fuel particles, which results in the occurrence of hot/cold spots and ash softening.

Larger sized fuel particles will remain at their original size for much longer in the bed before they reach the high temperatures needed for thermal degradation. For instance, on the basis of the energy balance for a single particle, it can be calculated that obtaining 800 °C under fluidization conditions requires tens of seconds for a 10 mm wood particle. This illustrates that the multiphase flow aspects of the bed could be influenced by the particles, which remain in their original state for a considerable period of bed operation.

Among the limited studies on the multiphase flow aspects of biomass fluidization, determination of characteristic fluidization velocities (Abdullah et al., 2003; Rao and Reddy, 2010; Rao and Bheemarasetti, 2001; Zhang et al., 2011), and the distribution and mixing pattern of biomass–inert materials (Berruti et al., 1988; Dos Santos and Goldstein, 2008; Shen et al., 2007; Yu et al., 2003) have been of particular interest to researchers. The impact of irregularly-shaped particles on the characteristics of the dilute and dense phases has received comparatively little attention, and it has generally been assumed that, due to the typically low ratio of biomass to sand in biomass processing units, the gas holdup in the bed is comparable to that of a bed of sand alone. In view of this, gas holdup or void fraction has mostly been studied in bubbling beds containing only relatively small biomass particles. The void fraction and its distribution in a two phase flow system are important in determining the interfacial area available for heat and mass transfer between the phases (Kiared et al., 1997). In addition, gas or solid holdup parameters are important for optimizing fluidization hydrodynamics and process efficiency (Franka and Heindel, 2009).

Using different materials, i.e., glass beads, ground corncob, and ground walnut shell whose sizes varied between 500 and 600 μm, Franka and Heindel (2009) found that fluidization among the different materials had similar behaviors with some notable differences. They applied X-ray computed tomography (CT) in order to determine the effects of side air injection, superficial gas velocity, and bed material on fluidization behavior and local time-averaged gas holdup. Of the three bed materials examined, ground corncob fluidization was the least affected by side air injection and showed the highest overall gas holdup while glass bead fluidization was much more affected by side air injection and had the lowest overall gas holdup. Escudero and Heindel (2011) showed also that for these materials, the gas holdup in the bed increased by decreasing the bed density. In a similar work performed in cold flow fluidized beds of 10.2 cm and 15.2 cm in diameter, Drake and Heindel (2012) concluded that bed mixing and uniformity were enhanced in both reactors when a lighter material was fluidized.

Zhang et al. (2009a) studied the bubbling fluidization of mixtures whose biomass-to-sand ratios varied from 1% to 3%. They used nearly cylindrical cotton stalk particles as the test biomass material, whose size and density are comparable to the particles used in the present study. By comparing pressure fluctuation amplitudes, they concluded that increasing biomass concentration led to a decreased probability for the growth and coalescence of bubbles (Zhang et al., 2010). In other words, they envisaged that thin-long biomass particles had a positive influence on the eruption of bubbles, a fact that became more pronounced when the concentration of biomass increased (Zhang et al., 2009b).

It is worth noting that, in a hot gas–solid fluidized bed, in-bed emission of volatile materials during combustion or gasification is responsible for the formation of “endogenous” volatile bubbles around the fuel particles. Endogenous bubbles enhance axial segregation of fuel particles at the bed surface (Solimene et al., 2003, 2012) and may influence the dynamic gas–solid distribution of the bed. The present study has been done under cold conditions and, thus, cannot assess this effect.

The present work aims to provide clear insight into the possible effects of large/light objects immersed in a bed of fine/dense particles on the gas distribution pattern in the bed. The gas fraction and gas holdup of the dilute (bubble) and dense (emulsion) phase profiles are studied at a given height of the bed in the presence of different quantities of biomass. Moreover, the dilute phase characteristics are measured using optical fiber probes for variable biomass loadings. The degree of bed expansion as a result of increasing gas velocity is used as a measure of the global gas holdup in the bed. All results are compared to baseline values of a pure-sand bed to determine the influence of irregularly-shaped, low-density particles on the multiphase flow features of a bubbling bed.

2. Experiments

All experiments are conducted in a cold fluidized bed consisting of a Plexiglas column with an internal diameter of 152 mm. The distributor plate is perforated with 1 mm diameter holes arranged in a triangular pitch. The flow rate of air is measured by a bench of rotameters and is introduced into the bed through a conical windbox. The bed material used in the experiments is sand with a particle size distribution (*PSD*) ranging from 300 to 500 μm. Synthetic biomass particles are fabricated from cylindrical wood rods cut into identical lengths. Table 1 contains more details of all materials used in this study. To investigate the effect of biomass weight fraction, four mixtures of different weight fractions of biomass in sand are studied, as detailed in Table 2. The mixture voidage of two solids differing in size exhibits a minimum at intermediate composition (Formisani et al., 2008, 2011; Yu and Standish, 1987). The porosity of sand is partially filled by the large biomass particles to a certain extent. Further increase in the volume fraction of biomass results in increasing the total voidage of the mixture because of the dominance of biomass particles having a much higher voidage than sand alone.

In all experiments, the static bed height is set to 228 mm ($H_0/D=1.5$). In order to start from a well-mixed condition, the sand and biomass measures are each equally divided into eight batches. Each batch of sand is mixed with a single batch of biomass. Finally, the content of all mixtures is sequentially added to the fluidization column.

The dynamic pressure fluctuations are monitored along the bed via several differential pressure transducers (OMEGA PX 272)

Table 1
Properties of materials used.

Material	Shape	D_p (mm)	L_p (mm)	ρ_p (kg/m^3)	ρ_b (kg/m^3)
Sand	Spherical	0.38	–	2650	1550
Biomass	Cylindrical	6.35	12.70	824	342