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Segregation of wood particles in a bubbling fluidized bed

B. Cluet [a], G. Mauviel [b,*], Y. Rogaume [a], O. Authier [c], A. Delebarre [d]

[a] LERMAB, Université de Lorraine, 27 rue Philippe Séguin, CS 60036, 88026 Epinal Cedex, France
[b] LRGP, CNRS, Université de Lorraine, 1 rue Granville, 54000 Nancy, France
[c] EDF R&D, 6 Quai Watier, 78400 Chatou, France
[d] LEMTA, CNRS, Université de Lorraine, 2 avenue de la Forêt de Haye, 54504 Vandoeuvre les Nancy, France

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ABSTRACT

Understanding wood segregation in bubbling fluidized beds is of importance for the global analysis, comprehensive modeling, and scale-up of bubbling fluidized bed biomass gasifiers. This study presents measurements of voidage and segregation taken during experiments in fluidized beds containing inert materials mixed with biomass particles. The features of the wood particles affect the bed axial homogeneity; a small particle size or a high density increase homogeneity. When gas fluidization velocity is low, the biomass particles are more segregated from olivine compared to the results achieved with larger velocities. In all experiments, a significant portion of the wood remains within the bed (50–80%), while the rest of the biomass floats at the bed surface. The experimental modeling accurately represents the voidage of the bed, with the exception of the upper part of the bed and the floating portion of the biomass particles. The results of the present study are in agreement with recent publications.

1. Introduction

The gasification or combustion of wood chips in fluidized beds necessitates the use of an inert bed material in which wood particles are introduced. These mixtures of inert materials with "wood/char" particles have complex fluidization behaviors. For instance, Delebarre et al. [1] pointed out that the minimum fluidization velocity concept is not straightforward for binary mixtures.

Understanding wood segregation in bubbling fluidized beds remains important for the global analysis, comprehensive modeling, and scale-up of bubbling fluidized bed gasifiers [2]. This phenomenon is strongly coupled with wood thermochemical reactions (pyrolysis and gasification) and bed hydrodynamics [3]. Segregation is likely to occur when there is a large difference in drag per unit weight between different solid particles.

The segregation of thick wood samples such as chips or pellets in sand beds has been less studied compared to pyrolysis/gasification/combustion kinetics [4–15] or fluidized bed hydrodynamics [1,3,16–21]. Some studies conducted on solid mixing in fluidized beds have focused on particles with the same density but different shapes or diameters [22–24] or particles with the same shape but different densities [22].

Norouzi et al. [25] studied the solid mixing pattern in a bubbling fluidized bed using a radioactive tracer with the same density as the bed material. This radioactive particle tracking method for visualizing the fluidized bed interior is an efficient technique, although it involves complex materials. Recently, Fotovat et al. [26] used the same experimental setup to analyze wood distribution in a sand fluidized bed; measurements were taken with a single tracer particle. They found a wood distribution all along the bed (Fig. 9) and better gas mixing with increasing velocity.

Wirsum et al. [27] studied light and large particles in sand using a magnetic field to track particles. Vertical mixing was improved by smaller and denser flotsams along with small sand particle diameters and high superficial velocities. Zhang et al. [28] investigated wood segregation and mixing in a fluidized bed. The results were based on three-layer sampling in a bed with a height of 300 mm. They also found that gas velocity affects segregation. In the regime of steady fluidization, mixing and segregation compete with each other, and there is a gas velocity that produces the maximum mixing for any given mixture.

Bruni et al. [29] studied the segregation of biomass particles in an incipient bubbling fluidized bed. Biomass particles tend to segregate at the upper part of the bed due to endogenous bubbles generated by devolatilization.

Some studies have been conducted on lateral mixing in fluidized beds [30–32]. Olsson et al. [31] investigated wood and sand mixing, demonstrating that lateral dispersion is strongly dependent on bubble

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[*] Corresponding author.
E-mail address: guillain.mauviel@univ-lorraine.fr (G. Mauviel).

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path. Wood concentration is more significant between bubble paths, and lateral dispersion is higher in the middle part of the bed than close to the surface. In addition, lateral dispersion is lower than vertical dispersion [30].

Segregation has often been quantitatively evaluated by a coefficient of segregation or a mixing index. The mixing index is defined by the ratio of the jetsam (i.e., solids that occupy the bottom of the bed) concentration in the upper layer to the average jetsam concentration [33]. Experimental evidence [34,35] has shown that the solid composition along the bed is generally not uniquely represented by this ratio. Hemati et al. [34] suggested using a relationship based on the integration of the concentration profile along the bed.

The aim of this work is to present an experimental study on axial segregation of thick wood in a relatively large lab-scale bubbling fluidized bed (i.e., diameter of 242 mm) to limit the wall effect (the ratio of the particle equivalent spherical diameter to the bed diameter is at least equal to 18). As discussed previously, some similar experimental studies have already been performed, but results were obtained mainly using single particle tracking or thick layer sampling. This study is based on simple pressure analyses and local bed sampling with 50 mm thick layers. The effects of several parameters related to wood particles are also studied (i.e., size, shape and density). Endogenous bubble formation is not studied herein, even though this phenomenon could impact segregation in real fluidized bed gasifiers.

2. Materials, methods and calculation

2.1. Materials

2.1.1. Experimental device

Experiments were carried out in a cold cylindrical fluidized bed composed of five parts: (i) an inlet gas system, (ii) a gas distributor, (iii) a fluidized bed column, (iv) a wood injection system, and (v) a data acquisition system. A schematic representation of the experimental setup is given in the Supplementary material (Fig. 1).

The fluidized bed was a cylindrical PMMA vessel with an inner diameter of 242 mm, a height of 2.5 m, and a thickness of 8 mm. This vessel was drilled on a vertical line each 50 mm to create pressure transducer inlets. The first hole was drilled 13 mm from the air distributor. Stainless steel pipes (8 mm external diameters, 3 mm internal diameters, and 40 mm lengths) were placed in each of these holes. To prevent bed leakage, filters were inserted in all of the pipes.

A PMMA distributor plate with a diameter of 242 mm and a height of 10 mm was perforated by 230 holes with diameters of 2.5 mm arranged in a square pitch in order to uniformly distribute the fluidization gas and avoid channeling and/or slugging. A cloth filter was placed over the air distributor plate to prevent the inert bed particles from falling down. The pressure drop of the air distributor was approximately 2500 Pa at 0.3 m/s.

An air box was included between the blower and the distributor plate to homogenize the air flow and obtain good fluidization. This plenum was a cylindrical PMMA vessel with an inner diameter of 242 mm and a height of 510 mm divided by a plate perforated by 5 mm holes. On the upper part of this plate, a layer of stainless steel marbles (15 mm diameter) was employed to homogenize air flow (Supplementary material Fig. 1).

The feeding gas was supplied by a side channel blower (MPR, 2.2 kW, 2900 rpm). The blower velocity was controlled by a variable frequency drive (Leroy Somer FMV2304). The velocity of the gas was measured by a hot wire anemometer (0–30 m/s) coupled to a computer for acquisition. The experimental setup was run between 0.04 m/s and 0.55 m/s; this velocity is equivalent to 0.3–6.8 of the minimum fluidization velocity (U_{mf}) depending on the olivine properties.

As shown in Fig. 1 of the Supplementary material, the bed was divided into 50 mm thick layers delimited by pressure pipes. The pressure acquisition system was composed of eight pressure transducers (Honeywell ascx0-5dn and ascx0-1dn) connected to a USB data acquisition device (NI USB-6009). The employed transducers were differential pressure sensors; one input was connected to the bed, while the second input was opened and thus was at ambient pressure.

2.1.2. Bed material

The inert bed material used in all experiments was composed of non-ferrous olivine (supplied by Sibelco Company North Cape Mineral, Norway). The olivine density and other characteristics are summarized in Table 1. Two types of olivine were used in this study: coarse olivine, which was sieved between 0.25 mm and 0.75 mm before each experiment, and fine olivine, which was passed through 0.25-mm mesh. The fine olivine fraction was fluidized at high velocity ($>7\ U_{mf}$) to remove the very fine particles.

These particle fractions are the same as those used in hot gasifiers. Using the same particles in a cold fluidized bed implies the failure to comply with the scale-up criteria proposed by Glicksman et al. [36]. However, as mentioned by Leckner et al. [37], it is not a simple task to find perfectly suitable particles to meet these criteria.

The olivine particle size distribution (Supplementary material Fig. 3) was measured by laser light scattering with a Malvern Mastersizer Hydro 2000 analyzer. The results obtained from this method were confirmed by comparison with microscope image analysis. These olivine particles were classified as Geldart type B because their size and density ranges were within 40–500 μm and 1400–4500 kg/m^3, respectively. Olivine sphericity was obtained from the image analysis of approximately 400 particles for each type of olivine. For each particle, three diameters were measured: (i) d_{min}, the smallest dimension of particle; (ii) d_{max}, the largest dimension of particle; and (iii) d_{mean}, the mean diameter of particle. Two ratios, $\frac{d_{mean}}{d_{max}}$ and $\frac{d_{min}}{d_{mean}}$, were calculated and are drawn on the Zingg diagram [38] modified by Lees [39] (Supplementary material Fig. 2).

2.1.3. Wood

Two types of wood were used in the segregation experiments: beech wood (685 kg/m^3), a typical wood for bioenergy applications, and balsa wood (190 kg/m^3), which has approximately the same density as char from beech wood. The advantage of balsa wood is that it is not friable compared to wood char.

Two particle shapes were selected for the experiments: cylindrical shape (dowels), with a sphericity equal to 0.77, and chip-like shape, with a sphericity equal to 0.50. These two shapes were chosen to assess the effect of particle shape on segregation. For balsa particles, two sizes were used to study the effect of size on segregation. All wood properties are summarized in Table 2 and Fig. 1.

Three geometrical characteristics (equivalent spherical diameter (d_v), sphericity (Φ_s), and effective diameter (d_{eff})) were calculated from the particle dimensions using Eqs. (1), (2), and (3), respectively:

$$d_v = 2\left(\frac{3\pi V_{particle}}{4}\right)^{\frac{1}{3}} \tag{1}$$

$$\Phi_s = \frac{\pi d_v^2}{S_{particle}} \tag{2}$$

$$d_{eff} = d_v \Phi_s. \tag{3}$$

Table 1
Olivine features.

Material	Particle density (kg/m^3)	Sauter diameter (μm)	Sphericity	U_{mf} (m/s)
Coarse olivine	3250	378	0.82	0.137
Fine olivine	3250	237	0.78	0.082