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DISTRIBUTION OF LARGE BIOMASS PARTICLES IN A SAND-BIOMASS FLUIDIZED BED: EXPERIMENTS AND MODELING

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ABSTRACT: The parameters linking Gibilaro and Rowe (G-R) model parameters to the operational conditions were improved on the basis of the experimental findings which describe the motion of flotsam particle as well as the characteristics of bubbling. Analysis of the experimental data obtained by the RPT technique revealed that the averaged rise velocity of biomass particles was around 0.2 times of the bubble velocity in the bed regardless of the biomass load or fluidization velocity. Shrinkage of bubbles in the presence of biomass particles was demonstrated using the optical probes.

INTRODUCTION

Nowadays, the use of biomass as a sustainable replacement of fossil fuels is drastically growing mainly because of the potential of biomass based units to mitigate the greenhouse gas emissions. Furthermore, the use of biomass in the form of municipal and agricultural waste as an energy resource relieves the problem of waste management in favor of developing localized energy production plants.

The most widespread technique to convert biomass into energy or value-added synthetic fuels is the thermo-chemical methods consisting of combustion, pyrolysis, gasification, and liquification. Several unique operational advantages, like fuel flexibility, intense solids mixing, and efficient heat transfer have made the fluidized bed the most efficient reactor option for all these processes. Nonetheless, fluidization of biomass particles is a cumbersome and even impossible task owing to their irregular size, density, and shape. An effective remedy is the addition of inert materials, like silica sand and alumina, as a fluidized medium in order to ease fluidization of biomass. Despite the facilitated fluidization of biomass under this condition, vastly different sizes, densities and shapes of inert materials and biomass result in some practical imperfections, such as the segregation of components. Usually, biomass particles tend to migrate to the top layers of the bed (flotsam behavior) because of their very low density, while the bottommost sections merely consist of fluidization medium (jetsam behavior). The occurrence of segregation can lead to noticeable change in the type and concentration profile of gasification products as well as the incidence of cold/hot spots and ash softening in biomass combustors/gasifiers.

In regard to the significant effect of segregation on the fluidized bed performance, it is always crucial to determine the distribution of biomass along the bed under diverse operating conditions, such as different fluidization velocities or loads of biomass as the parameters affecting the extent of segregation. Developing models, which predict the mixing/segregation of jetsam components, has been attempted by many researchers. These models have been mostly based on the two-phase theory of fluidization by including some additional terms to describe the segregation

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mechanisms. Gibilaro and Rowe (1) were pioneers of developing fluidization models in which mixing and segregation have been taken into account. They constructed a simple equilibrium model to predict jetsam volume concentration against bed height, based on a one-dimensional system consisting of bulk and wake phases, where jetsam was preferentially discharged by rising bubbles (2). Subsequent models were mainly developed to modify some assumptions considered in the G-R model and provide a link between some of the model parameters and fluid dynamic characteristics of the bed (3-5). Bilbao et al. (5,6) adapted the G-R model to represent the hydrodynamic behavior of a fluidized bed consisting of sand and straw. For this purpose, they implemented some major modifications in order to take into account the peculiar physical properties of straw.

In light of the recent findings on the characteristics of fluidization features of irregular particles, it has been attempted in the present study to predict the concentration profile of the biomass particles along the bed. In situ distribution of biomass versus bed height has been explored by the Radioactive Particle Tracking (RPT) method. It was a more precise and realistic approach compared to the inaccurate and burdensome "freezing procedure" traditionally used for the same purpose (7). Furthermore, this technique was exploited to investigate the validity of assumptions made in previous studies to model the mixing/segregation of binary mixtures.

EXPERIMENTS

All experiments were conducted in a cold conventional fluidized bed consisting of a Plexiglas column with a 152 mm internal diameter. A perforated plate containing around 160 holes 1 mm in diameter arranged in a triangular pitch was used as a distributor. The fluidization medium used in the experiments was sand whose size distribution ranged from 100 to 1000 μm. Biomass particles were provided from birch cylindrical rods cut into identical lengths of small particles. Table 1 contains more details of materials used in this work. The eight fraction of biomass in the investigated mixtures varied from 2 to 16%.

Table 1. Properties of materials used

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

In all experiments the height of the static bed was set to 225 mm (H/D=1.5). To simulate the well-mixed state as the initial fluidization condition, the entire amount of sand and biomass required for each run was equally divided into eight batches. Then, the content of each batch of sand was mixed with that of a batch of biomass. Finally, the content of all mixtures, which had been prepared in this way, was poured one by one into the fluidization column.

Bubbling characteristics of beds of sand alone as well as the binary mixtures were studied by placing two identical reflective optical probes at bed heights of 175 and 200 mm above the distributor. The probes were inserted parallel to each other 76 mm (D/2) into the bed. The relevant signals were acquired with LabVIEW ® with a sampling rate of 512 Hz for 3 minutes. A MATLAB ® program was developed after introducing some modifications to the algorithm introduced by Rüdisüli et al. (8) to evaluate the size and velocity of bubbles.

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The tracer used for RPT experiments was made by embedding a tiny compound of Scandium oxide and epoxy resin in one of the biomass particles so that the size and density of final tracer did not deviate from that of the original particle. Such a tracer could mimic well the motion of biomass particles during fluidization. The tracer was then activated in the SLOWPOKE nuclear reactor of École Polytechnique up to an activity of 70 µCi. The produced isotope ^{46}Sc emitted γ-rays, which were counted by 12 NaI scintillation detectors arranged at 3 levels.

The number of γ-rays detected by each detector was acquired by a high speed data acquisition system and registered by a personal computer. These counts were used later to calculate the coordinates of the tracer. Details of the system calibration and the inverse reconstruction strategy for tracer position rendition can be found elsewhere (9). In each experiment the movement of the tracer that was placed into the bed with other particles was tracked every 10 ms for about 6 hours and, finally, more than two million data points were acquired.

In order to obtain the concentration profile of biomass through the RPT technique, the bed space was imaginarily compartmentalized by means of several slices. The ratio of occurrence of the tracer in a specific slice to the total number of occurrences, i.e. the total number of instantaneous positions acquired, was considered as the corresponding concentration of that compartment. The volume fraction of biomass in each slice was calculated by knowing the total mass and density of biomass mixed with sand.

MODEL DESCRIPTION AND DISCUSSION

The principals of the following model have been based on the G-R model, however, in the current model the concentration profile of the flotsam component is described, unlike the G-R and other common models in which the jetsam behavior has been explained.

Considering that the bed is composed of bulk and wake phases, it has been assumed that the wake phase is devoid of biomass particles because of their extreme size. Indeed, the rise of biomass particles mainly occurs due to the intermittent jerks produced by a drift mechanism as a consequence of successive bubble passes. Moreover, since bubbles travel preferentially in the central region of the bed, a large scale circulation is also felt by the flotsam particles. Jetsam particles, however, rise in the wake phase and descend in the bulk phase. Moreover, they can be exchanged between wake and bubble phases. As reported by other researchers (5, 10), contribution of the jetsam axial mixing and segregation propensity to the material balances for solids mixing is negligible under the conditions of biomass fluidization, thus they have not been considered in the proposed model. Fig. 1 depicts a diagram of a horizontal layer of the bed of dZ thickness to which the mass balances of both phases have been applied. The mathematical expression of each term is as follows:

Fluidization medium (sand in our experimental systems) rises along the bed in the wake of bubbles and sinks in the bulk (emulsion) phase. Thus, the flow of rising sand, i.e., Ψ_F^b (m^3/s) is formulated as below.

$$\Psi_F^b = U_b \delta_b F_w (1 - \varepsilon_F) A \quad (1)$$

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where ε_F is the voidage of the emulsion phase of a bed containing sand only. It has been calculated by the Cui et al. (11) correlation taking into consideration the effect of gas velocity on the ε_F (Eq. 2).

$$\varepsilon_F = \varepsilon_{mf} + 0.2 - 0.059\exp\left[-\frac{(U-U_{ib})}{0.429}\right] \quad (2)$$

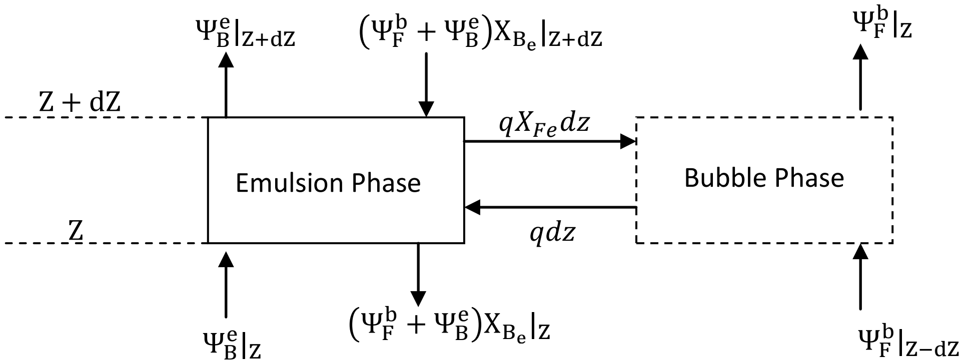

Fig. 1. Diagram of the model

The volume fraction occupied by bubbles has been calculated using Eq. 3. Y indicates the degree of deviation of the bed from the "two-phase theory". Since sand is the dominant component in the investigated mixtures in terms of weight and volume, Y=0.7 was chosen as a typical assumption for the Geldart B particles.

$$\delta_b = \frac{Y(U-U_{ib})}{U_b} \quad (3)$$

As previously reported (12), the presence of biomass particles could delay the onset of bubbling compared to the bed of sand alone. Thus, it was reasonable to use the initial bubbling velocity (U_{ib}) instead of U_{mf} of sand in order to evaluate the excess gas velocity. It was found that U_{ib} was linearly correlated with the weight fraction of the biomass (x_{Bm}) systems studied.

On the basis of the analysis of the biomass rise velocity realized through post-processing of the RPT data, it was found that the height-averaged rise velocity of biomass particles was around 0.2 times the average bubble rise velocity along the bed (Fig. 2). It is consistent with the findings of Soria-Verdugo et al. (13). In view of the rise of biomass particles in the emulsion phase, the rising flow of biomass, i.e., Ψ_B^e (m^3/s) is obtained by Eq. 4.

$$\Psi_B^e = 0.2U_b(1-\delta_b)(1-\varepsilon_{M_e})X_{B_e}A \quad (4)$$

ε_{M_e} is the voidage of the emulsion phase in a mixture containing fluidization medium and biomass particles and as proposed by Bilbao et al. (5), it can be calculated using Eq. 5 based on the fact that the fluidization medium occupies the voidage between biomass particles.

$$\varepsilon_{M_e} = 1 - \frac{1-\varepsilon_B}{1-X_{F_e}} \quad (5)$$

Eq. 5 is valid when $X_{B_e} > \frac{1-\varepsilon_B}{1-\varepsilon_F}$. For lower values of X_{B_e}, it is assumed that the voidage of the mixture emulsion phase (ε_{M_e}) equals to the voidage of a bed of fluidization medium alone (ε_F).

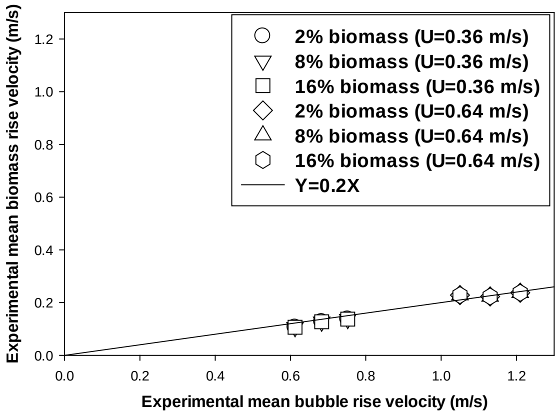

Fig. 2. Mean rising velocities of biomass particles along the bed obtained through the RPT technique and compared with the velocity of bubbles

The exchange rate of the fluidization medium between wake and emulsion phases per unit of bed height can be described by Eq. 6.

$$q = K_w \delta_b (1 - \varepsilon_F) A \quad (6)$$

Assuming that the exchange coefficient between the constitutive phases (K_w) is not affected by the biomass particles, the correlation introduced by Hoffmann et al. (14) was chosen to calculate K_w from properties of the bed as pointed out by Radmanesh et al. (15).

$$K_w = \frac{0.081}{2\varepsilon_{mf} d_b} \quad (7)$$

One of the common assumptions in modeling binary mixtures is that the bubbling characteristics of the system are those of a bed of only fluidization medium. In other words, owing to a lack of experimental data, the probable effect of irregular particles on the bubbles has been neglected. Fig. 3 elucidates the difference between the size of bubbles in beds containing sand alone and mixtures of sand and biomass on the basis of analysis performed on the optical probe signals. As seen in the figure, at low bubbling velocities (U<0.3 m/s), size of bubbles was almost the same for the systems studied. By increasing the fluidization velocity, however, the difference between bubble sizes became more recognizable. In fact, bubbles shrank in systems containing biomass.

From a holistic point of view, the most suitable correlations for predicting bubble size and velocity at small to moderate gas velocities (U<1 m/s) for the investigated systems were correlations of Darton et al. (16) (Eq. 8), and Davidson and Harison (17) (Eq. 9), respectively. It should be remarked that other correlations, such as those developed by Choi et al. (18), Cai et al. (19), and Horio and Nonaka (20), predict values smaller than the bubble size measured experimentally and therefore their use in the model led to inappropriate results.

$$d_b = 0.54 g^{-0.2} (U - U_{ib})^{0.4} (Z + 4A_c^{0.5})^{0.8} \quad (8)$$

$$U_b = 0.711\sqrt{g d_b} + (U - U_{ib}) \quad (9)$$

A mass balance on a slice of the bed for both wake and emulsion phases can be summarized as follows:

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$$\frac{dX_{B_e}}{dz} = \frac{qX_{B_e}}{(\Psi_F^b + \Psi_B^e)} \qquad \text{B.C. } X_{B_e} = X_{B_{e0}} \ @ \ Z=0 \tag{10}$$

The axial volume fraction of biomass (X_B) is derived from X_{B_e} values through the following equation.

$$X_B = \frac{(1-\delta_b)(1-\varepsilon_{M_e})X_{B_e}}{(1-\delta_b)(1-\varepsilon_{M_e}) + F_b\delta_b(1-\varepsilon_F)} \tag{11}$$

A computer program was developed to fit the experimental data with the above equations. To do so, the bed was virtually discretized into successive layers. Eq. 10 was then converted into linear equations using a finite difference scheme and solved numerically for each layer. The boundary value ($X_{B_{e0}}$) was the only adjustable parameter. In light of the flotsam behavior of biomass particles, a rational initial value for this parameter was the minimum of X_B obtained from the experiments.

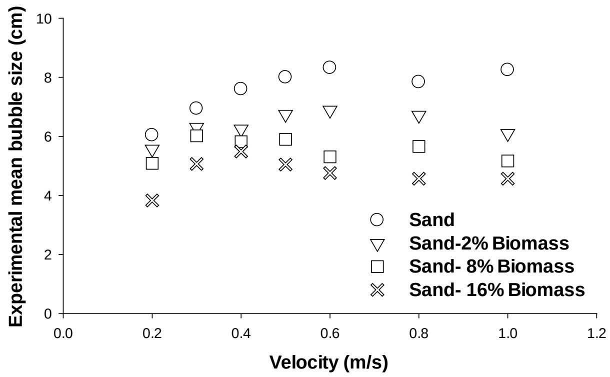

Fig. 3. Comparison of mean bubble size for a bed of sand alone and mixtures containing biomass at different fluidization velocities

Fig. 4 shows the experimental profile of biomass concentration along the bed compared to the model proposed at two different fluidization velocities. As mentioned earlier, this profile was obtained by post-processing of the RPT data through the virtual slicing of the bed and computing the ratio of occurrence of the tracer in a specific slice to the total number of occurrences, i.e. the total number of recorded instantaneous positions. These values were then related to the volume fractions of biomass in each slice.

As seen below, a good fit can be considered satisfactory, particularly when the load of biomass is low. By increasing the weight fraction of biomass, however, the fitting quality slightly declines mainly because of the considerable deviation of the actual bubble size from what is predicted by the Darton et al. correlation. Indeed, it is expected that the prediction capacity of the model will improve significantly if the effect of biomass on the bubbling behavior of systems could be taken into account more accurately. It was reasonable to relate $X_{B_{e0}}$ to the fluidization velocity (U) and the weight fraction of biomass in the mixture (x_{Bm}). Applying a multivariable data fitting reveals that $X_{B_{e0}}$ is proportional to x_{Bm} and U as below.

$$X_{B_{e0}} = kx_{Bm}U^6 \tag{12}$$

Eq. 12 denotes the significant role of fluidization velocity in enhancing well distribution of biomass along the bed. Experimental data and a model in which this proportionality was considered as the boundary condition have been compared in

Fig. 5. As seen, use of Eq.12 in the suggested model for estimating $X_{B_{eo}}$ brings about acceptable prediction of biomass distribution profile along the bed.

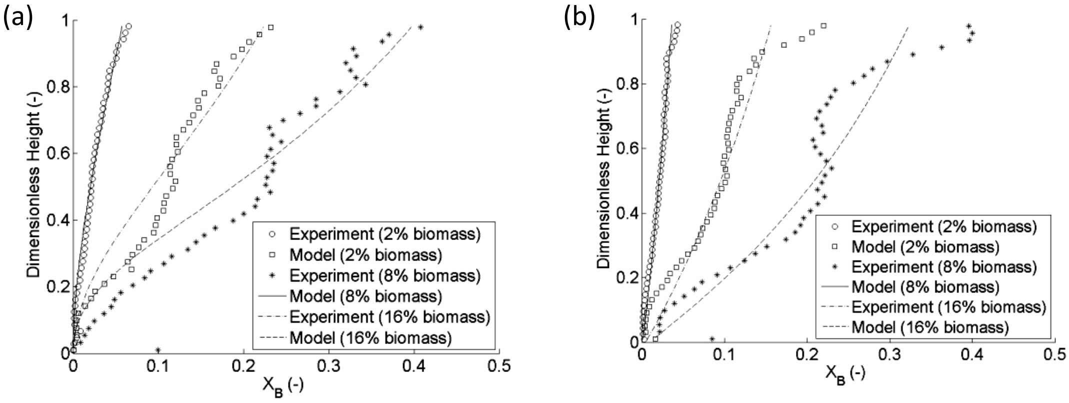

Fig. 4. Experimental and modeled volume fraction of biomass (X_B) vs. dimensionless height at a)U=0.36 m/s b)U=0.64 m/s when $X_{B_{eo}}$ was the only adjustable parameter

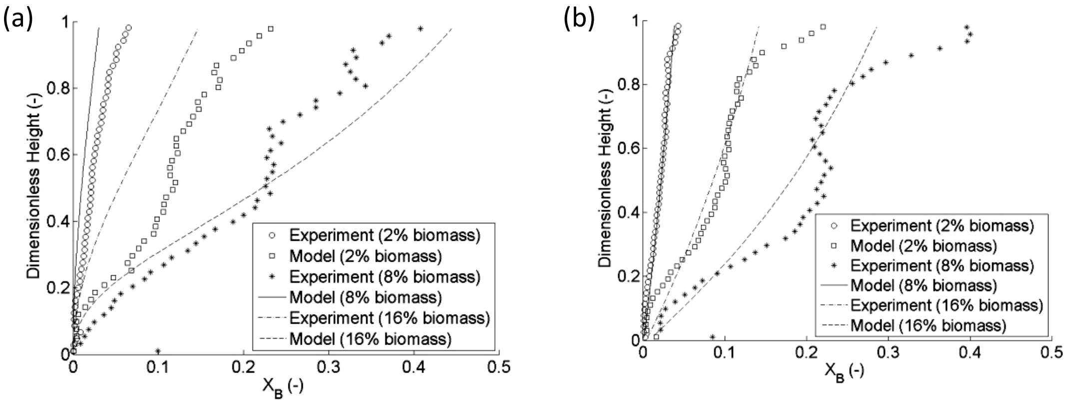

Fig. 5. Experimental and modeled volume fraction of biomass (X_B) vs. dimensionless height at a)U=0.36 m/s b)U=0.64 m/s when Eq. 12 was used to estimate $X_{B_{eo}}$

CONCLUSION

The parameters relating terms of the G-R model to the operational conditions were improved on the basis of the experimental findings describing the motion of the flotsam particle as well as the characteristics of bubbling. Analysis of the experimental data obtained by the RPT technique revealed that the averaged rise velocity of biomass particles was around 0.2 times the bubble velocity in the bed regardless of the biomass load or fluidization velocity. Shrinkage of bubbles in the presence of biomass particles was demonstrated using the optical probes. It was also found that the correlation of Darton et al. could predict bubble size more precisely in the investigated systems in comparison with other corresponding correlations. The accordance of the modified model results with the *in situ* experimental data was reasonably satisfactory.

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NOTATION

A: Cross-sectional area of the bed (m^2)
A_C: Catchment area of a hole in the distributor (m^2)
d_b: Bubble diameter (m)
F_w: Ratio of bubble wake volume to bubble volume (-)
K_W: Exchange coefficient between wake and emulsion phases (s^{-1})
q: Wake-emulsion exchange coefficient (m^2s^{-1})
U: Superficial gas velocity (ms^{-1})
U_b: Bubble rise velocity (ms^{-1})
U_{ib}: Initial bubbling velocity (ms^{-1})
x_{Bm}: Weight fraction of biomass in the mixture (-)
$\mathbf{X_B}$: Volume fraction of biomass in a specific layer (-)
$\mathbf{X_{B_e}}$: Volume fraction of biomass in the emulsion phase of a specific layer (-)
$\mathbf{X_{B_{e0}}}$: Volume fraction of biomass in the emulsion phase at Z=0 (-)
$\mathbf{X_{F_e}}$: Volume fraction of fluidization medium in the emulsion phase of a specific layer (-)
Z: Height (m)
$\mathbf{\Psi_B^e}$: Volumetric flow rate of biomass in the emulsion phase (m^3s-^{1})
$\mathbf{\Psi_F^b}$: Volumetric flow rate of fluidization medium in the bubble phase (m^3s-^{1})
Y: Deviation factor from two-phase theory of fluidization (-)
δ_b: Volume fraction of bubbles in bed (-)
$\mathbf{\varepsilon_{M_e}}$: Void fraction of emulsion phase in a biomass-fluidization medium mixture (-)
ε_B: Void fraction of a bed of biomass alone (-)
ε_F: Void fraction of a bed of fluidization medium alone (-)
ε_{mf}: ε_F at minimum fluidization conditions (-)

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