Experimental verification of drag laws for binary, gas-fluidized systems

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ABSTRACT

Axial species segregation measurements were carried out in a fluidized bed with a binary mixture of Geldart Group B particles. Several bed loadings with glass–polystyrene and polystyrene–polystyrene mixtures were investigated. The experimental results were then compared with MP-PIC numerical simulations with two drag laws for polydisperse systems, following the method described in the companion work by Leboreiro *et al.* [1]. The first drag law is an ad-hoc extension of a monodisperse drag law; the second one explicitly accounts for the binary nature of the system.

In glass–polystyrene experiments, the polystyrene particles—larger and more massive than the glass ones—act as flotsam; in polystyrene–polystyrene systems the fines act as flotsam. The ad-hoc extension of the monodisperse drag law captures the qualitative segregation profile in the glass–polystyrene systems better, but tends to overpredict the segregation in systems with dissimilar species' concentrations; the binary drag law consistently predicts almost full to full segregation for the corresponding systems. In the case of polystyrene–polystyrene systems, where the species differ only in size, the roles of the two drag laws reverse, with the binary drag law predicting a mild concentration profile and the extended monodisperse drag law predicting full segregation.

The observed discrepancies may be related to differences in bed dynamics between the experimental and simulated systems and/or limitations of the monodisperse drag law. Preliminary results from granular kinetic theory, together with comparisons between the bubbling patterns of the experiments and simulations, are currently being applied to evaluate the relative abilities of the drag laws.

KEYWORDS: Segregation, mixing, gas-fluidized, drag law, binary, simulation, Geldart B.

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I INTRODUCTION

Since their introduction in chemical industries, fluidized beds have been researched extensively in an effort to improve the various processes that rely on them. Due to the large number of industrial processes that depend on the fluidization of fine and coarse particles (as in coal combustors for electricity generation [2] and catalytic cracking of petroleum), a strong emphasis has been placed on understanding the differences in fluidization behavior of monodisperse systems due to particle size (i.e., the fact that fine particles fluidize differently than coarse ones). Less emphasis has been placed on bridging the gap between understanding single-species behavior and predicting multiple-species interactions important to pharmaceutical and chemical industries alike (as in drug manufacturing and production of high-grade alumina, Al_2O_3, or titania, TiO_2).

A better understanding of the bed dynamics, including mixing and segregation of two or more species, is of particular relevance to the pharmaceutical industry, where it is very important to guarantee the uniform blending of small drug particles into a matrix of larger ingredients. Segregation in fluidized beds has been extensively studied during the past several decades. Numerous segregation mechanisms (percolation, granular temperature gradients, bubbling, etc.) have been reported and the complex physics involved cannot be easily generalized. In systems where fine dusts are present, segregation has been linked to elutriation of the fines, which is in turn related to the bubbling patterns in the bed [3]. Rowe *et al.* [4] were the first to name the sinking component of a binary system *jetsam* and the rising component *flotsam*. They analyzed segregation by size difference and concluded that the component separation is a consequence of bubble motion, as previously suggested by Zenz and Othmer [3]. The competing effects of solids being carried to the top of the bed by the wake of bubbles and particles descending through the emulsion phase and percolating as a result of gravity produce a circulation that tends to gather jetsam at the bottom of the bed and flotsam at the top [5]. Denser or larger particles tend to act as jetsam while lighter or smaller particles tend to act as flotsam [6], although for some conditions a layer inversion has been observed [7, 8].

The long-term goal of the current effort is to better understand segregation as it relates to elutriation. To date, the study of elutriating systems has been limited to empirical correlations that unfortunately fail to accurately predict key features of practical systems (like the entrainment rate), with uncertainties that range from twofold to hundredfold in some cases [9]. No first-principles model has been created that takes into account the complex interactions among gravity, flow drag, gas-phase turbulence, and particle collisions, to mention a few factors. As a first step toward our goal, we target a binary experimental system in which the effects of drag force dominate. Such a system serves as a test bed that enables a critical comparison of existing drag laws for polydisperse systems. We are focusing on two drag laws: the first, following Gidaspow [10], is a combination of the Ergun [11] and the Wen and Yu [12] drag laws; the second is a modification of the first by a multiplicative factor proposed by van der Hoef *et al.* [13] that accounts for the binary nature of the system. A companion work [1] found, via simulation, that the form of the drag law has a significant impact on the qualitative nature of size segregation. Of the two drag laws tested, the one without the van der Hoef *et al.* correction predicts full segregation for all gas velocities, with the small particles always sitting on top; the corrected drag law predicts a well-mixed state at high gas velocities, with increasing segregation for moderate to low velocities. Only a handful of researchers have reported combined experimental and computational investigations of segregation in binary gas-fluidized systems [14, 15], and their primary focus was not to target the impact of

Table 1. Properties of the particles used.

Material	Legend	d (μm)	ρ (kg/m^3)	m (μg)	ϕ	u_{mf} (cm/s)
Lead-free glass	GL	106–125	2476	1.41	0.891	1.8
Polystyrene						
small	PS$_s$	212–250	1064	7.73	—	—
medium	PS$_m$	250–300	1064	14.1	1.068	4.0
large	PS$_l$	300–355	1064	23.8	1.086	5.4

drag force laws. Our objective is to determine, through a systematic experimental and numerical analysis of segregation, the relative abilities of these drag laws in predicting species segregation.

II EXPERIMENTAL PROCEDURE

In the present effort, we look at the segregation of two Geldart B species in a Plexiglas column 18.5 cm in diameter and fluidized by air at atmospheric pressures and temperatures. The species are detailed in Table 1. The diameters d correspond to the cut between two consecutive standard sieve openings. The density ρ was determined with a Quantachrome Multipycnometer; the mass m of an average particle is also listed. A Mott Corporation 316 stainless steel porous plate with an average porosity of 10 μm and a 1.6 mm thickness acts as distributor plate. A Yaskawa V7 variable frequency drive controls a Fuji Electric VFD5 regenerative blower that provides the air for fluidization. The superficial velocity u is determined based on upstream measurements from a Lambda Square Oripac 4150-P orifice plate flow meter. Table 1 also includes a calculated sphericity ϕ. This sphericity is used in Ergun's equation as a multiplicative factor to the mean diameter $(d_{min}+d_{max})/2$ such that the measured minimum fluidization velocity u_{mf} of the individual species is correctly calculated. The sphericity accounts for both shape variations of the particles and polydispersity about the mean, which explains why values greater than unity are possible.

Several glass–polystyrene and polystyrene–polystyrene mixtures were characterized and select results are shown in Table 2. The velocities u_{mf} and bed heights H_{mf} at minimum fluidization correspond to the point of intersection of the packed bed slope and the bed weight in the respective ΔP–U diagram. The maximum packing fractions ε_{max} are determined form the average bed height of three to five fully mixed, settled beds at a certain loading.

Axial species segregation measurements have been performed for several superficial velocities in beds composed of 4 kg of glass and 4 kg of polystyrene (50/50 GL/PS$_m$). A trial run was performed at a superficial velocity of 12 cm/s, well above u_{mf} for either material, for 30 minutes.

Table 2. Fluidization characteristics of the mixes used.

Materials (by mass)	u_{mf} (cm/s)	H_{mf} (cm)	ε_{max}
50/50 GL/PS$_m$	4.1	31.3	0.656
75/25 GL/PS$_m$	2.3	21.5	0.586
46/54 PS$_s$/PS$_l$	6.0	35.0	0.613

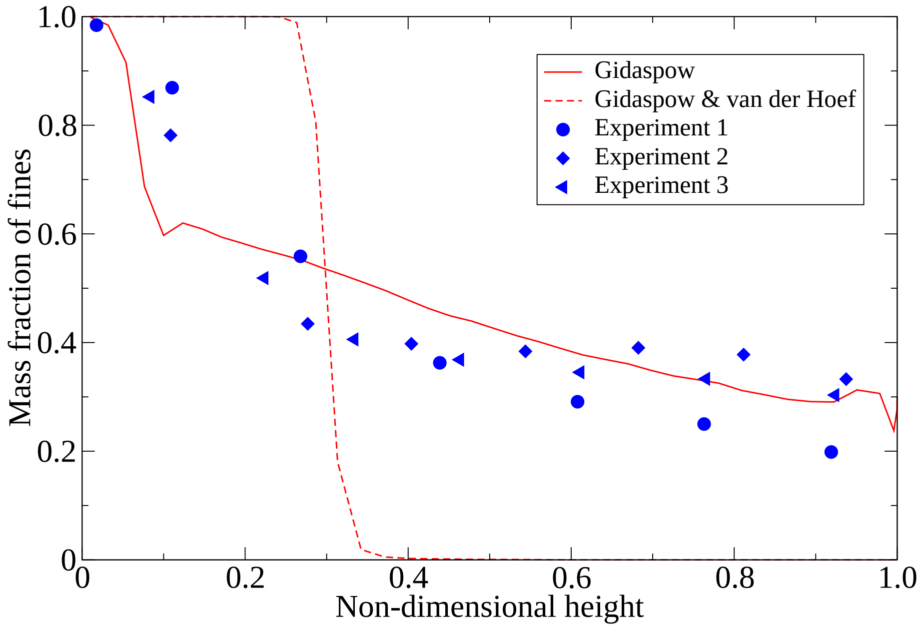

Figure 1. Segregation trials for a mixture of 4 kg glass and 4 kg polystyrene (50/50 GL/PS$_m$) fluidized at a superficial gas velocity $u = 4.5\ \mathrm{cm/s}$ ($1.1u_{mf}$). The lines represent numerical simulations according to the method described by Leboreiro *et al.* [1].

The air supply was rapidly shut off and the "frozen" bed was subsequently sliced in 4 cm bands and analyzed by sieving. The analysis confirmed a well-mixed composition. In order to guarantee repeatable initial conditions, a 30-minute mixing stage at 12 cm/s was used for all subsequent experiments.

III RESULTS AND DISCUSSION

After the initial mixing period described above, the gas velocity was adjusted to a target value and the system was allowed to stabilize prior to freezing and sectioning. Care was taken to guarantee that the stabilization time was long enough to achieve a steady state. Comparisons among stabilization times of 15 min, 30 min, 1 hr, and 3 hr indicate that 1 hr is sufficient stabilization time for a steady state. For 50/50 GL/PS$_m$ runs at 4.5 cm/s ($1.1u_{mf}$) a strong, uniform bubbling of the bed was observed during operation. Figure 1 shows the segregation results from three replicas of this experiment. The bed was found to be partially mixed, i.e., there was a layer of flotsam at the top, a layer of jetsam at the bottom, and a middle section where both components were present; in these experiments, the glass—the fines—acts as jetsam. Compare the segregation pattern in Figure 1 to the one shown in Figure 2, corresponding to a 46/54 PS$_s$/PS$_l$ system at a comparable gas velocity of 6.8 cm/s ($1.1u_{mf}$). In the polystyrene case, the fines act as flotsam. Figures 1 and 2 also include curves corresponding to the predictions from the numerical simulations [10, 13], computed using the method described by Leboreiro *et al.* [1].

The drag law based on the stitching of Ergun [11] and Wen and Yu [12] proposed by Gidaspow performs quite well for the 50/50 GL/PS$_m$ case (Figure 1), despite not explicitly accounting for the binary nature of the system. The same drag law, corrected by the multiplicative factor of van der Hoef *et al.*, incorrectly predicts full segregation. For the 46/54 PS$_s$/PS$_l$ system (Figure 2),

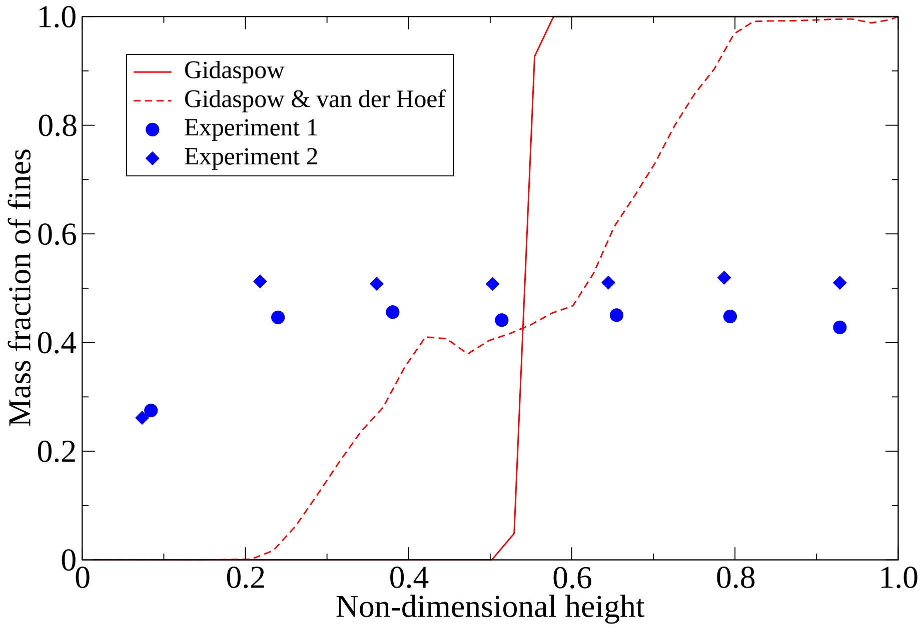

Figure 2. Like *Figure 1*, for 2.74 kg PS_s and 3.26 kg PS_l (46/54 PS_s/PS_l); $u = 6.8$ cm/s ($1.1u_{mf}$).

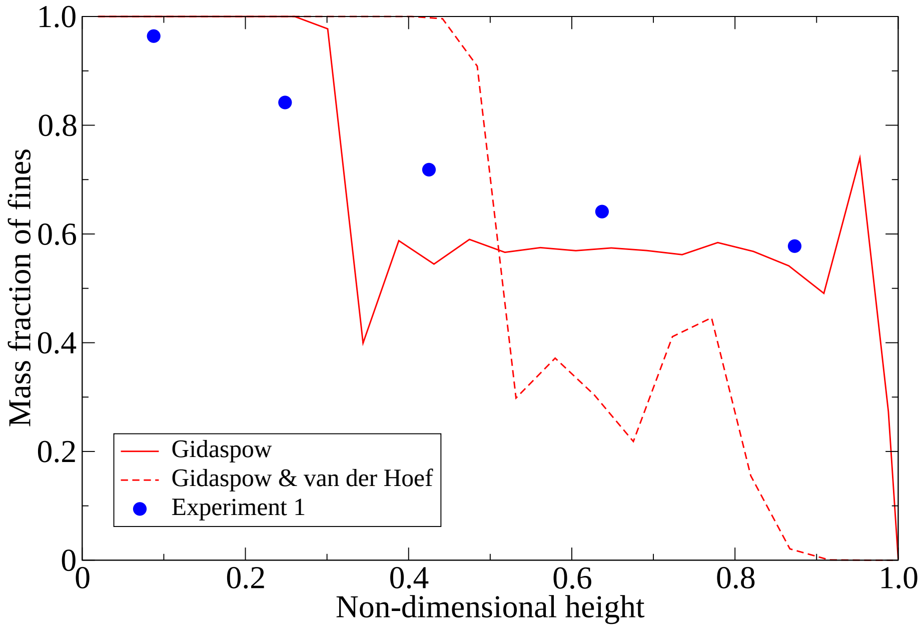

Figure 3. Like *Figure 1*, for 4.5 kg GL and 1.5 kg PS_m (75/25 GL/PS_m); $u = 2.8$ cm/s ($1.2u_{mf}$).

neither method successfully predicts the experimental results and, to a certain extent, a role reversal occurs, with the Gidaspow drag law now predicting a full segregation and the van der Hoef *et al.* drag law predicting a somewhat mixed system that does not quantitatively capture the mixed state shown by the experiments.

Experiments were also run with a high concentration of glass (75/25 GL/PS_m) at various gas velocities. Two representative cases are shown in Figure 3, for a gas velocity of 2.8 cm/s ($1.2u_{mf}$),

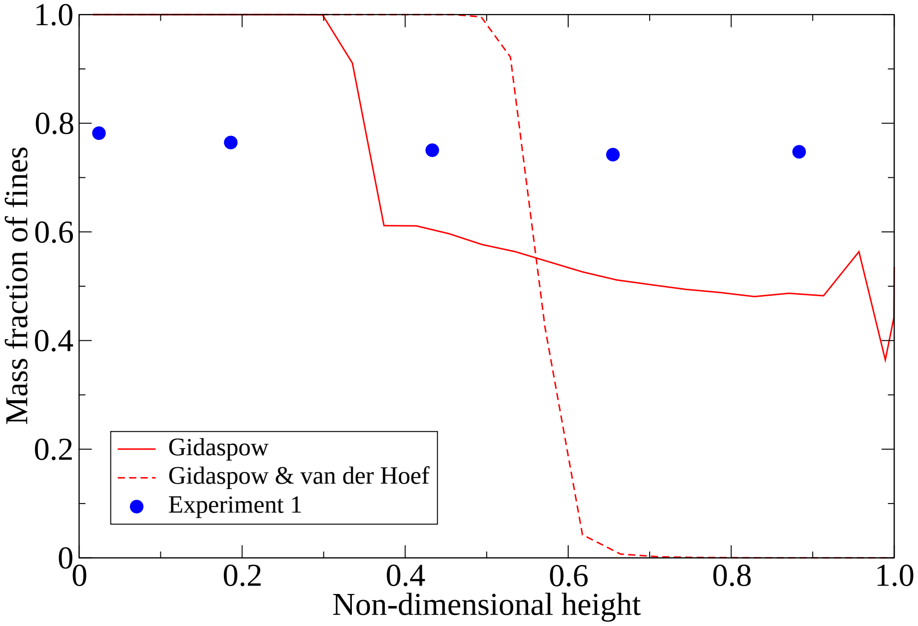

Figure 4. Like *Figure 1*, 4.5 kg GL and 1.5 kg PS_m (75/25 GL/PS_m); $u = 5.0$ cm/s ($2.2u_{mf}$).

and in Figure 4, for a gas velocity of 5.0 cm/s ($2.2u_{mf}$). For the gas velocity just above u_{mf}, where bubbles are barely present in the system, the bed slowly segregates into a layered mixture with an increasing glass concentration toward the bottom. The segregation process is visually observable over the first few minutes of the experimental run, with jetsam rapidly sinking through the voids in the flotsam. The observed partly segregated state is confirmed by bed slicing and is shown in Figure 3. The numerical simulations with either drag law predict this segregation as well, with the Gidaspow doing a better job and the van der Hoef *et al.* correction predicting full segregation. For a somewhat higher gas velocity of $2.2u_{mf}$ the experiments show a mostly-mixed bed while the simulations from either drag law predict segregation, with the van der Hoef *et al.* drag law predicting almost total segregation.

IV CONCLUDING REMARKS

Collectively, the experimental and numerical results point out the strong impact of the drag law formulation on the predicted segregation patterns. Discrepancies between the experiments and simulations with the two drag law formulations may be attributed to a number of factors, including limitations of existing drag laws to adquately capture bubbling behavior in monodisperse beds, simplified solid-phase stress treatment, and limitations of the simulation method associated with the prediction of time scales. Each of these factors will be discussed in the presentation, along with a simplified kinetic-theory analysis of the systems examined [8], in order to shed light on the dominating mechanisms. Additional experiments and simulations are underway in order to fully evaluate the relative abilities of the drag laws.

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