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Segregation of equal-sized particles of different densities in a vertically vibrated fluidized bed

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Abstract

The present work experimentally studies the influence of vibration and gas velocity on the density-induced segregation of particles in a pseudo−2D vibrated fluidized bed. One half of the particles of the bed are ballotini spheres of density 2500 kg/m^3 and the other half are heavier ceramic particles of density 4100 kg/m^3 or 6000 kg/m^3. Digital Image Analysis is used to characterize the rate and extent of particle mixing with time for different gas velocities, vibration amplitudes and frequencies. The results of the experiments indicate that the vibration strength and the gas velocity have an important effect on both the evolution and the final extent of density-induced particle segregation. It was observed that by introducing vertical vibration to a bed that is fluidized close to minimum fluidization conditions the rate of segregation and the final segregation index of a mixture of light and dense particles is enhanced. However, for vibration strengths greater than a critical value around 3−4, the degree of segregation decreases due to a more vigorous three dimensional mixing of particles in the bed.

Keywords: Fluidized bed, Pseudo-2D, Vibration, Segregation

1. Introduction

Many operations in the chemical and energy-conversion industries rely on the fluidization of heterogeneous materials. During fluidization, particles of different densities can segregate even if they are of the same size [1]. Segregation can be used to separate granular materials, but it should be avoided in processes requiring well mixed particles and a uniform distribution of the fluidizing gas [2]. Thus, an understanding of segregation on a fundamental level is paramount to identify effective measures to control it. One approach to control segregation is mechanical vibration of the bed vessel. In mechanically vibrated fluidized beds, the oscillation movement of the bed vessel is transmitted to the interior of the bed and affects the dynamics of

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its dense and bubble phases [3, 4, 5, 6]. This can be used to modify (i.e. increase or decrease) the rate and extent of particle segregation in a fluidized bed.

In recent years, several works have analyzed the effect of vibration on particle segregation in processes involving gas fluidized beds, such as coal beneficiation [7, 8], fine coal cleaning [9] and lignite cleaning [10]. In Luo et al. [7] and He et al. [8], a dense medium vibrated fluidized bed was employed for the separation of fine coal particles of different densities and sizes (<6 mm in [7] and 1-3 mm, 3-6 mm in [8]). In Luo et al. [7], the segregation degree was measured after 20 s of separation time, whereas in He et al. [8] the effect of the separation time was experimentally investigated by collecting the lignite of the bed at different time instants. These works showed that the separation performance for coal was improved when the gas and vibration operative conditions of the vibrated fluidized bed were optimized.

In Yang et al. [9], the segregation of coal particles (size distributions $3-6$ mm and $1-3$ mm and densities ranging from 1200 to 2400 kg/m^3) was experimentally studied. The effect of several factors, such as the gas superficial velocity, bed height, vibration intensity and segregation time was investigated. It was observed that the segregation degree reached a maximum value when varying the vibration strength at a fixed gas superficial velocity. It was also shown that the maximum degree of segregation was obtained for a gas superficial velocity just above the minimum bubbling velocity of the bed. The segregation degree decreased when increasing the bed height, which was attributed to the weaker effect of vibration in the upper section of the bed and the presence of large bubbles. These bubbles promote large-scale particle circulations that decrease segregation.

In Zhao et al. [10], an experimental study of the dependence of segregation of lignite particles (1-6 mm) on the gas superficial velocity and vibration amplitude and frequency was performed. For each of the experiments, the bed was operated for 2 min, which ensured close to steady state values of the segregation index. It was concluded that vibration of the bed enhances segregation of particles owing to their differences in size and density, especially if the bed is fluidized slightly above the minimum fluidization velocity. It was also indicated in Zhao et al. [10] that, for high vibration amplitudes, the segregation quality decreases due to the high circulation rate of particles in the bed.

In the previously mentioned works, the segregation phenomenon was simultaneously induced by differences on the size and the density of non-spherical particles, making difficult to elucidate the actual role of the particle density on the observed segregation. Also, due to the nature of the experiment, the temporal evolution of particle segregation was estimated by taking ensemble average of independent experiments under the same operating conditions. Thus, the results of the segregation index were limited to a reduced number of time instants, which are insufficient for obtaining a detailed time evolution of the segregation phenomenon. In addition, there is little literature available concerning the effect of vibration on density-induced segregation with equally sized particles in a fluidized bed. In Sun et al. [11], the segregation induced by density of a mixture of particles of 1400 and 2000 kg/m^3 and similar size (d_p = 3 mm) in a gas fluidized bed of 0.15 x

0.7 m^2 was numerically studied by means of 2D DEM simulations. When varying the operative conditions of the bed, they observed that segregation reached a maximum for certain vibration amplitudes, frequencies and gas superficial velocities. The time evolution of segregation during the 20 seconds of simulation time was analysed. The final segregation index at the end of the simulation was found to decrease if the vibration amplitude, frequency or the superficial gas velocity were further increased beyond their optimal values.

To the authors' best knowledge, experimental works studying segregation (i.e. variation with time and final value) in a vibrated fluidized bed filled with spherical particles with approximately the same particle diameter and different particle densities are currently lacking. These experiments could be very useful for understanding segregation in vibrated fluidized beds, developing new models and validating numerical simulation. Thus, the present work aims to characterize experimentally density driven segregation in a vertically vibrated fluidized bed comprising a mixture of spherical particles of two different densities and similar diameter.

2. Experimental setup

The segregation experiments were conducted in a pseudo−2D bed of dimensions 0.2 m width, 0.5 m height and 0.01 m thickness (see Figure 1). The walls of the bed were constructed of anti-static PMMA in order to allow optical access to the bed. The fluidizing gas was air, which was continuously introduced at the bottom of the bed through a perforated plate distributor with 50 holes of 0.7 mm of diameter. The air flow rate was controlled by a pressure regulator and it was measured by means of a mass flow controller (Analyt−MTC 35816). A gas humidifier was situated between the mass flow meter and the bed plenum to eliminate antistatic forces. The bed was mounted onto an electrodynamic shaker (Labworks Inc., ET-139), which generated vibration in the form of a vertical sinusoidal displacement $\delta = A \sin(2\pi f t)$. A controller (Labworks Inc. VL−144), an amplifier (Labworks Inc., PA−138−1) and an accelerometer (PCB Piezotronics Inc., J352C33) were used to control and monitor the semi-amplitude, A, and frequency, f, of vibration.

Four square pieces of paper were glued on the front wall of the bed as a reference to obtain the instantaneous position of the bed vessel. The front part of the bed was uniformly illuminated by two LED spotlights symmetrically disposed at each side of the bed.

The bed material was glass particles of density ρ_L = 2500 kg/m^3 mixed with the same volume of white ceramic particles of either ρ_D = 6000 kg/m^3 (Mixture 1) or ρ_D = 4100 kg/m^3 (Mixture 2). Spherical particles were used. To obtain an equal volume mixture of light and dense particles, the bed was first filled with a layer (0.055 m) of ceramic particles. Subsequently, an additional layer (0.055 m) of glass particles was added on top of the previous bed. Thus, the total static bed height was H_0 = 0.11 m. Table 1 shows the properties of each of the mixtures employed in the experiments.

[Figure 1 about here.]

[Table 1 about here.]

In Table 1, $U_{mf,L}$ and $U_{mf,D}$ are, respectively, the minimum fluidization velocity of the light and dense particles in the mixture. The minimum fluidization of each type of particles was determined experimentally. In the present work, the gas superficial velocity, U_0, will be normalized with the minimum fluidization velocity, $U_{mf,D}$, of the denser particles in the mixture, i.e. particles of $\rho_D = 6000$ kg/m^3 in Mixture 1 and particles of $\rho_D = 4100$ kg/m^3 in Mixture 2, since dense particles determine the onset of complete fluidization of the mixture.

Each experiment started with the light (black) and dense (white) particles randomly mixed, and the air valve was opened synchronously with the onset of vibration ($t = 0$). A high speed CCD camera (Optronics CL 600 x2/M) was used to record images of the bed through its front wall at a frame rate of 50 images per second. Digital Image Analysis (DIA) of the captured images was used to characterize the rate and extent of particle segregation with time. The experiments were stopped when no variation on the distribution of the black and white particles was identified.

In order to study separately the influence of the amplitude and frequency of the vibrations and the gas superficial velocity on the segregation of the mixtures, several conditions were tested in the experiments. For each of the mixtures, a reference case with $f = 15$ Hz and $A = 4$ mm and a relative superficial velocity of $U_0/U_{mf,D} = 0.91$ for the Mixture 1 and $U_0/U_{mf,D} = 1.16$ for the Mixture 2 was selected (see bold numbers in Table 2). These experimental velocities corresponded to conditions in which segregation could be clearly identified in the mixture when the bed vessel was vibrated. Note that for Mixture 1, the gas superficial velocity of the reference case is below $U_{mf,D}$ whereas for Mixture 2, the gas velocity of the reference case exceeds the minimum fluidization velocity of the denser particles. Thus, the reference cases in the two Mixtures investigate the effect of vibration with two different flow conditions. In each of the experiments, only one parameter was changed at a time. Table 2 shows the different vibration frequencies, amplitudes and gas superficial velocities of the experiments conducted. The table also contains the vibration strength, which is defined as $\Lambda = (2\pi f)^2 A/g$.

[Table 2 about here.]

3. Data Processing

3.1. Segregation Index

To quantify the extent of particle segregation with time, the Lacey index [12] was used. The Lacey index is based on a statistical analysis conceived for discrete system. In the images of the bed, particles are difficult to distinguish individually and, instead, they appear like a speckle pattern. Therefore, an adaptation of the Lacey index to particle images is proposed here.

Firstly, the bed image is divided in $N_c = 1950$ cells of 17 x 17 (N_x x N_y) pixels (i.e. cells of 8 mm side) in the horizontal and vertical directions. A sensitivity analysis showed a small variation of the results with N_c for the range of number of cells employed in this work. Secondly, the normalized area concentration of the denser, white, particles in each cell is calculated as:

$$c_k = \frac{1}{N_x N_y} \sum_{x_k=1}^{N_x} \sum_{y_k=1}^{N_y} \frac{G_{x_k,y_k} - G_{min}}{G_{max} - G_{min}} \phi_k \tag{1}$$

Where ϕ_k is the fraction of the k^{th} cell occupied by the bed particles (i.e. $\phi_k = 1$ if the cell is fully occupied by particles and $\phi_k = 0$ if there are no particles in the cell), G_{x_k,y_k} is the grayscale level of each of the pixels in the cell (from $G = 0$ black to $G = 255$ white). For each image of the experiments $G_{min} = 0$, as the brightness level of the black particles is $G = 0$, and $G_{max} = min(255; \overline{G} + \sigma_G)$. $\overline{G}$ and σ_G are, respectively, the mean value and the standard deviation of the grayscale level for all the pixels of the bed in the image (excluding the freeboard). A change of system of reference to one moving with the bed vessel is performed so that the bed does not move in this new system of reference and the location of the cells in the bed is preserved along the data processing. This is done by following the position of the reference squares shown in Figure 1 and displacing the image vertically to preserve their location.

Thirdly, the variance of the concentration of the white particles in all the cells of the bed is defined as:

$$\sigma_c^2 = \frac{1}{N_c - 1} \sum_{k=1}^{N_c} (c_k - \overline{c})^2 \tag{2}$$

where $\overline{c}$ is the average concentration of white particles in the whole bed.

$$\overline{c} = \frac{1}{N_c} \sum_{k=1}^{N_c} c_k \tag{3}$$

Finally, the segregation index, based on Lacey's mixing index is defined at each instant as:

$$SI = 1 - \frac{\sigma_0^2 - \sigma_c^2}{\sigma_0^2 - \sigma_R^2} \tag{4}$$

In Equation 4, $\sigma_R^2 = \overline{c}(1 - \overline{c})/n_p$ is the variance for a bed with a perfectly random mixture of white and black particles, $\sigma_0^2 = \overline{c}(1 - \overline{c})$ is the variance for a bed with a completely segregated mixture of particles and n_p is the average number of particles observed in the area of the sampling cells.

4. Results and Discussion

4.1. General bed behaviour and segregation regimes

Figure 2(a,b) shows two examples of how density induced segregation of particles evolves with time once the fluidization air and vibration have been switched on simultaneously ($t = 0$). The figure contains snapshots of the bed every 10 seconds showing the distribution of light and dense particles. The normalized mean concentration of heavier (white) particles, c_k, horizontally averaged along the bed width, is also presented at the right side of each snapshot.

For the case of $f = 15$ Hz and $A = 4$ mm in Figure 2(a), a clear progression of segregation of light and dense particles with time can be observed. The increase of segregation with time (viz. segregation rate) is higher at the beginning of the experiment, reaching a segregation pattern in which the light particles can be found in the upper half of the bed and the denser particles are in the lower half of the bed. As segregation progresses, the thickness of the layer of light particles in the upper half of the bed increases with time. Note that segregation at $t = 30$ s in Figure 2(a) is not yet completed and slowly increases due to the fact that some light (black) particles remain trapped among the dense (white) particles and they progressively ascend to the upper half of the bed. For the case of $f = 20$ Hz and $A = 4$ mm, Figure 2(b) shows that the progression of segregation is very reduced and reaches a stable value around $SI = 0.31$. In this case, it was observed in the experiment that the particle mixture presented a downward movement close to the front and rear walls of the bed and ascended through the central section of the bed. However, the full three dimensional movement of particles is restricted by the limited transverse thickness of the bed. Thus, the thickness of the bed may influence the segregation index when three dimensional movement of particles occurs. The upwards motion of particles in the central section of the bed was observed visually from a lateral perspective while carrying out the experiments. Segregation can be reversed towards complete mixing if only vibration is applied to the bed without introducing gas through the distributor. This is shown in Figure 2(c) for $f = 15$ Hz and $A = 4$ mm and an initially segregated distribution with light particles in the upper half of the bed and the dense particles in the lower half. In this experiment, a three dimensional recirculation movement appeared, similarly to Figure 2(b) but stronger. This reveals that by switching on gas fluidization at velocities close to $U_{mf,D}$ in a vibrated bed, density segregation is induced.

[Figure 2 about here.]

In the experiments without vibration for $U/U_{mf,D} = 0.91$, gas alone was unable to segregate the mixture. Figure 2(d) shows the evolution of particle segregation for a larger gas superficial velocity ($U_0/U_{mf,D} = 1.07$) in which gas alone is able to segregate the mixture, but with a reduced rate. This indicates that the fluidization with gas, when coupled to vibration, is the main driving factor that leads to segregation in these experiments.

A qualitative study using sequences of images as shown in Figure 2 was undertaken for different vibration conditions to identify the phenomena involved in density induced segregation. The results are sketched in Figure 3, which shows the effect of increasing the vibration strength, for the same gas superficial velocity, in the segregation of light and dense particles observed in the experiments of the vibrated fluidized bed. Three different regimes of density-induced segregation of particles were detected, which are described below.

[Figure 3 about here.]

4.1.1. Vibration-enhanced segregation

At low vibration strengths, Figure 3(a), vibration enhances segregation as it cooperates with the segregation caused by the gas superficial velocity for $U_0/U_{mf,D} \sim 1$, creating larger voids between the particles in the bed. In this vibration-enhanced segregation, which is the situation also described in Figure 2(a), dense particles percolate easier through these voids due to their larger weight and move downwards as the light particles move upwards. In this case, if the gas superficial velocity is sufficiently large, bubbles appear. Due to the smaller minimum fluidization velocity of the lighter particles, the bubbles are larger in the region in which these particles are present. For example, in Figure 2(a), bubbles only appear in the upper black layer of the bed. However, they cannot be recognized easily in the figure due to the low contrast between the black particles and the background color of the bed vessel. Bubbles also promote segregation because dense particles rain inside the bubble at a higher velocity than the light particles. A further increase of the gas superficial velocity may decrease the final segregation extent as dense particles can be dragged up by bubbles to the upper half of the bed.

4.1.2. Vibration-induced mixing

When the vibration strength is large enough, the transport of particles is dominated by the convective movement of the bed bulk induced by vibration of the bed vessel, as in vibrated beds without gas [13, 14, 15], similar to the behaviour encountered in Figure 2(c) when no gas is injected in the bed. This effect is sketched in Figure 3(b). Here, both the impact of the bed with the distributor and the interaction of the particles with the front and rear walls of the bed feed energy into the system that is not counterbalanced by the gas phase. A three dimensional convective motion with the light and dense particles descending at a similar velocity close to the front and rear walls, and ascending through the central section of the bed, was observed. This vibration-induced mixing precludes the formation of bubbles for the range of gas superficial velocities tested in the experiments. The segregation of the mixture was quite reduced and only a small layer of light particles become segregated on top of the bed (e.g. Figure 2(b) at 30 s).

4.1.3. Transitional segregation

Interestingly, for intermediate values of the vibration strength, the behaviours in Figures 3(a) and 3(b) can be observed in the same experiment before and after a transition time, t_{tr}, as indicated in Figure 3(c).

During the first seconds of the experiment, vibration-induced mixing, with downward movement of the particles close to the front and rear walls of the bed appeared ($t < t_{tr}$ in Figure 3). Here, the particle behaviour is similar to that shown in Figure 3(b). However, dense particles move downward slightly faster than light particles, which promotes a gradual segregation of the bed that slowly creates a layer of light particles on top of the bed. This increases the average density of the remaining mixture placed below. That seems to stop the convective motion that is enhanced by vibration and the front and rear walls that are in close proximity. In turn, the vibration-enhanced segregation mechanism described in Figure 3(a) is triggered, causing the separation of the light and dense particles after this transition ($t > t_{tr}$ in Figure 3(b)). From that moment on, the bed behaviour is similar to that shown in Figure 2(a). The segregation index in this transitional segregation mode presents two clearly distinguishable regions, as will be shown later in Figures 5(b) and 5(c).

4.2. Segregation index

Figure 4 shows the time evolution of the segregation index of Mixture 1 (ρ_D = 6000 kg/m^3) for different vibration conditions and gas superficial velocities. Firstly, Figures 4(a) and 4(b) show the effect of vibration on segregation as a function of the gas superficial velocity. Curves of the segregation index are smoothed out with a moving average to eliminate the perturbation on the segregation index caused by bubbling and the oscillation of the bed surface. It can be clearly observed in Figure 4(a) that vibration of a gas fluidized bed improves the segregation of the mixture by increasing the final segregation index (i.e. steady value for large t) and decreasing the time required to reach it. Gas without vibration of the bed vessel was unable to segregate appreciably the mixture for the gas superficial velocities, U_0, below 1.01 $U_{mf,D}$, and these results are not presented in Figure 4(a). The introduction of vibration produces the separation of the mixture even for $U_0/U_{mf,D} < 1$ as a result of the effects commented in the previous section for the regime of vibration−enhanced segregation (Figure 3(a)). In particular, according to Figure 4(b), the qualitative evolution of segregation with time is the same for $U_0/U_{mf,D} \geq 0.91$. At the beginning of the experiment the rate of segregation is high because vibration-induced segregation is the driving mechanism. Once high SI values have been reached, the rate of segregation progressively decreases as the bed approaches the maximum SI. These observations made are similar to the results reported by Sun et al. [11], in which density segregation is modeled using discrete element model (DEM) simulations (see Section 1). Generally, for $U_0/U_{mf,D} \geq 0.91$ in Figure 4(b), at the beginning of the experiment the rate of segregation increases when increasing the gas superficial velocity. However, for gas superficial velocities smaller than $U_0/U_{mf,D}$ <0.91 the gas velocity together with the vibration were unable to completely segregate the mixture (SI <0.8). Also in Figure 4(b), the final index of particle segregation reached at the end of the experiment increases with the gas superficial velocity.

Figures 4(c) and 4(d) show, respectively, the effect of the vibration frequency and amplitude on the segregation index for a case in which the gas alone is unable to segregate the mixture (i.e. $U_0/U_{mf,D}$ = 0.91). It can be observed that an increase of either the vibration amplitude or frequency promotes a decrease of the segregation rate ($d(SI)/dt$) after the first 10 s of the experiment. The final segregation index decreases significantly for high vibration amplitudes (A = 5 mm) and, especially, for high vibration frequencies (f =20 Hz), as observed in Figure 2(b). In this case, the final segregation index diminishes due to the effect of vibration-induced mixing described in the previous section (Figure 3(b)).

[Figure 4 about here.]

Figure 5 shows the evolution of segregation with time for the Mixture 2 (ρ_D =4100 kg/m^3). Similarly to Figure 4, both increasing the gas superficial velocity and adding vibration to the system increase the segregation of the mixture (the last effect due to vibration-enhanced segregation). The rate of segregation of particles in Mixture 2 shows a similar behaviour as the one plotted in Figure 4; that is, the rate of segregation increases when increasing the superficial velocity of the fluidizing gas. However, for high superficial gas velocities the rate of segregation between the different experiments changes only slightly and the final value of the segregation index decreases when increasing $U_0/U_{mf,D}$ (see Figure 5(a, b)). In these cases, the bubbles rising in the upper half of the bed are able to drag upwards white (dense) particles, and that counteracts the density segregation. This behaviour was also observed when increasing the gas superficial velocity in Mixture 1 beyond $U_0/U_{mf,D} > 1.12$.

The transitional segregation regime qualitatively described in Figure 3(c) is observed in Figure 5(b) for the gas superficial velocity equal to $U_0/U_{mf,D} = 1.1$ and in Figure 5(c) for a vibration amplitude of A = 5 mm. If the gas superficial velocity is large enough, the segregation effect induced by the gas is able to overcome the vibration-induced mixing and the mixture is segregated. However, either by decreasing the gas superficial velocity or by increasing the vibration strength, vibration-induced mixing becomes the dominant mechanism in the bed. Thus, the transitional segregation mode appears as an intermediate state between vibration-induced mixing, observed for $U_0/U_{mf,D} < 1.1$ in Figure 5(b), and vibration-induced segregation, observed for $U_0/U_{mf,D} > 1.1$ and for $A < 5$ mm in Figures 5(b) and (c), respectively. Figure 5 shows that the range of $U_0/U_{mf,D}$ in which the transitional segregation region occurs is relatively narrow. In the transitional segregation regime, vibration-induced mixing is counteracting density induced segregation. During the beginning of the experiment (10 s $< t <$ 40 s), there is a convective movement of the bed bulk and, hence, vibration−induced mixing is the prevalent mechanism affecting particle behaviour in the bed. In this situation, the segregation index grows slowly following a nearly linear slope. Around t_{tr} = 45 s in Figure 5(b) and t = 35 s in Figure 5(c), the increased weight of the mixture in the lower half of the bed is enough to stop the three dimensional convective movement of the bed bulk and promote a change of the segregation mechanism to vibration-enhanced segregation (see Figure 3(c)). From this instant on, the segregation rate increases and approaches an asymptotic value similar to that encountered at higher gas superficial velocities or low vibration strengths.

[Figure 5 about here.]

Figure 6 shows the time evolution of the segregation index as a function of the vibration strength, Λ, by separately varying the vibration amplitude and frequency (see Table 2), for 6 different time instants and an example of gas superficial velocity chosen for the reference case, i.e. $U_0/U_{mf,D} = 0.91$ (Mixture 1) and $U_0/U_{mf,D} = 1.16$ (Mixture 2). The data correspond to the experiments of Figures 4(c, d) and Figures 5(c, d). It can be observed in Figure 6 that the segregation index is influenced strongly by the vibration strength. As mentioned previously, vibration and the gas superficial velocity can exhibit counteracting effects on segregation. The segregation index increases when introducing vibrational energy into the system (i.e. Λ is increased), this effect has been also observed in other experimental [10] and numerical [11] studies. This can be seen clearly in Figure 6(b) for Mixture 2 and $0 \leq \Lambda \leq 3$. At low vibration intensities, vibration promotes a decrease of the effective U_{mf}, which increases the void fraction of the bed and enhances segregation similarly as an increase of the gas superficial velocity. For Mixture 1 (Figure 6(a)), values at have not been included because the introduction of only gas was unable to segregate the mixture for $U_0/U_{mf,D}$ = 0.91. However, at higher vibrational intensities, the vibration induced a convective motion of particles in the bed leading to vibration-induced mixing, which in turn, decreased the segregation index. This is evidenced in Figure 6(a) and 6(b), showing a dramatic decrease of the segregation index for $\Lambda \geq 6$. Note that different combinations of A and f can yield the same vibration strength Λ. Previous works concerned with segregation in vibrated fluidized beds [10], evidenced different values of the segregation index for the same Λ and different combinations of A and f. However, the superficial gas velocity at which the segregation index reaches a maximum is very similar in these combinations of f and A. Hence, for the system studied, Λ is a key parameter controlling segregation.

[Figure 6 about here.]

Figure 7 presents the final value of the segregation index, *viz.* the SI reached at large t (i.e. when the rate of segregation is very small) as a function of the gas superficial velocity and the vibration strength for the two mixtures. As observed before in Figures 4 and 5, Figure 7(a) shows that vibration extends the range of gas superficial velocities for which the final segregation of the mixture is relatively high ($SI > 0.8$). For Mixture 2, the segregation index reaches a maximum value for a superficial velocity slightly above the minimum fluidization velocity ($U_0/U_{mf,D}$=1.15). This observation is in agreement with previous studies [9, 10, 11]. Only for superficial velocities higher than $U_0/U_{mf,D} = 1.15$ the segregation index of Mixture 2 decreased with increasing superficial gas velocity. Figure 7(b) shows that, for the vibrated fluidized bed studied here, the maximum value of the SI remained unchanged regardless of the vibration strength. Only for $\Lambda \gtrsim 3.6$, the final segregation index decreases dramatically for Mixture 1. In Mixture 2, the critical value was higher, i.e. $\Lambda \sim 4.5$. This difference in the critical values obtained may be attributed to the higher velocity ratio, $U_0/U_{mf,D}$, used for Mixture 2. This requires a greater vibration strength to counteract vibration-induced segregation by the vibration-induced mixing effect.

[Figure 7 about here.]

Figure 8 plots the time required to reach 90% of the final segregation index for each of the experiments conducted. Figure 8 only includes experiments in which the mixture attains a final segregation index $SI > 0.6$. From Figure 8(a) it can be observed that by passing from no vibration to vibration conditions, the time employed to segregate the particles is reduced in both mixtures. The difference between the segregation times of the experiments with no vibration and vibration decreases when $U_0/U_{mf,D}$ is increased. This is because at large gas superficial velocities, the effect of vibration on segregation is comparatively smaller than the effect of the gas. Also, for similar gas velocity ratios, $U_0/U_{mf,D}$, the segregation time of Mixture 1 is considerably shorter than Mixture 2 due to the higher density ratio (ρ_D/ρ_L) of the former.

The effect of the vibration strength on the segregation time is depicted in Figure 8(b). There exists a value of the vibration strength above which the introduction of vibration increases the time needed to segregate the mixture. In Mixture 1, the minimum segregation time occurs for $\Lambda = 2.7$ and progressively increases when increasing the vibration strength. The increase of the segregation time at large Λ occurs despite the fact that the final segregation index decreases with Λ (see Figure 7(b)). For Mixture 2 the trend is clearer. The segregation time decreased for increasing vibration strengths. However, the segregation time shows a sudden increase for $\Lambda = 4.5$ since, for that experiment, a transitional-segregation regime occurs and that increases the segregation time (see Figures 3 and 5).

[Figure 8 about here.]

5. Conclusions

The effect of vibration and gas superficial velocity on density-induced particle segregation in a vertically vibrated fluidized bed was studied experimentally. A segregation index was developed to quantify segregation from DIA data. The results show that vibration enhances segregation in a gas fluidized bed in cases when the gas alone is unable to separate the particles of different density. The experiments revealed further that the temporal evolution and final extent of segregation is directly influenced by the vibration strength. It was observed that the gas superficial velocity and the vibration of the bed vessel possess counteracting effects on segregation. An increase of the gas superficial velocity increases segregation and facilitates dense particle percolation through light particles. This increased the extent of segregation as long as there is no vigorous bubbling in the bed. Low vibration strengths increase the excess of fluidization gas, enhancing in turn segregation (vibration−enhanced segregation). The introduction of strong vibrations in the system promotes convective movements of the bed promoting particle mixing (vibration-induced mixing) and counteracting the segregating effect of the gas superficial velocity. This decreases the final extent of the particle segregation. At intermediate vibration strengths, a transitional segregation regime occurs in which an initial vibration-induced mixing transitions to vibration−enhanced segregation. Generally, it was observed that a mixture with a higher density ratio decreases the time required for segregation. The experiments indicate that, for each mixture, there is an optimum combination of vibration strength and gas superficial velocity to maximize segregation. In this optimum combination regime, vibration does not counteract gas-induced effects and allows the percolation (segregation) of the denser particles while limiting re-mixing effects.

Nomenclature

A = vertical vibration amplitude (m)

c = concentration of dense particles (−)

d_p = particle diameter (mm)

f = vibration frequency (Hz)

g = gravity constant (m/s^2)

G = gray-scale level (−)

H_0 = static bed height (m)

n_p = number of particles in a cell (-)

N_c = number of cells (-)

N_x = number of pixels horizontally (-)

N_y = number of pixels vertically (-)

SI = segregation index (-)

t = time (s)

t_{tr} = transition time (s)

U_0 = superficial gas velocity (m/s)

U_{mf} = superficial gas velocity (m/s)

x = horizontal direction (m)

y = vertical direction (m)

Greek letters

δ = vibration displacement (−)

Λ = vibration strength (−)

ρ = solids density (kg/m^3)

σ = standard deviation

ϕ_k = fraction of a cell $(-)$

Subscripts

D = dense particles

L = light particles

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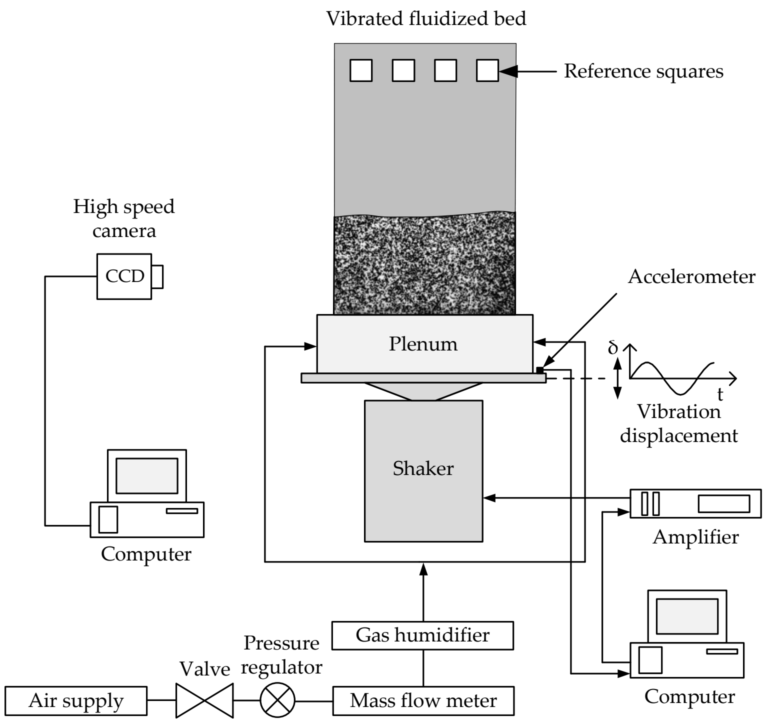

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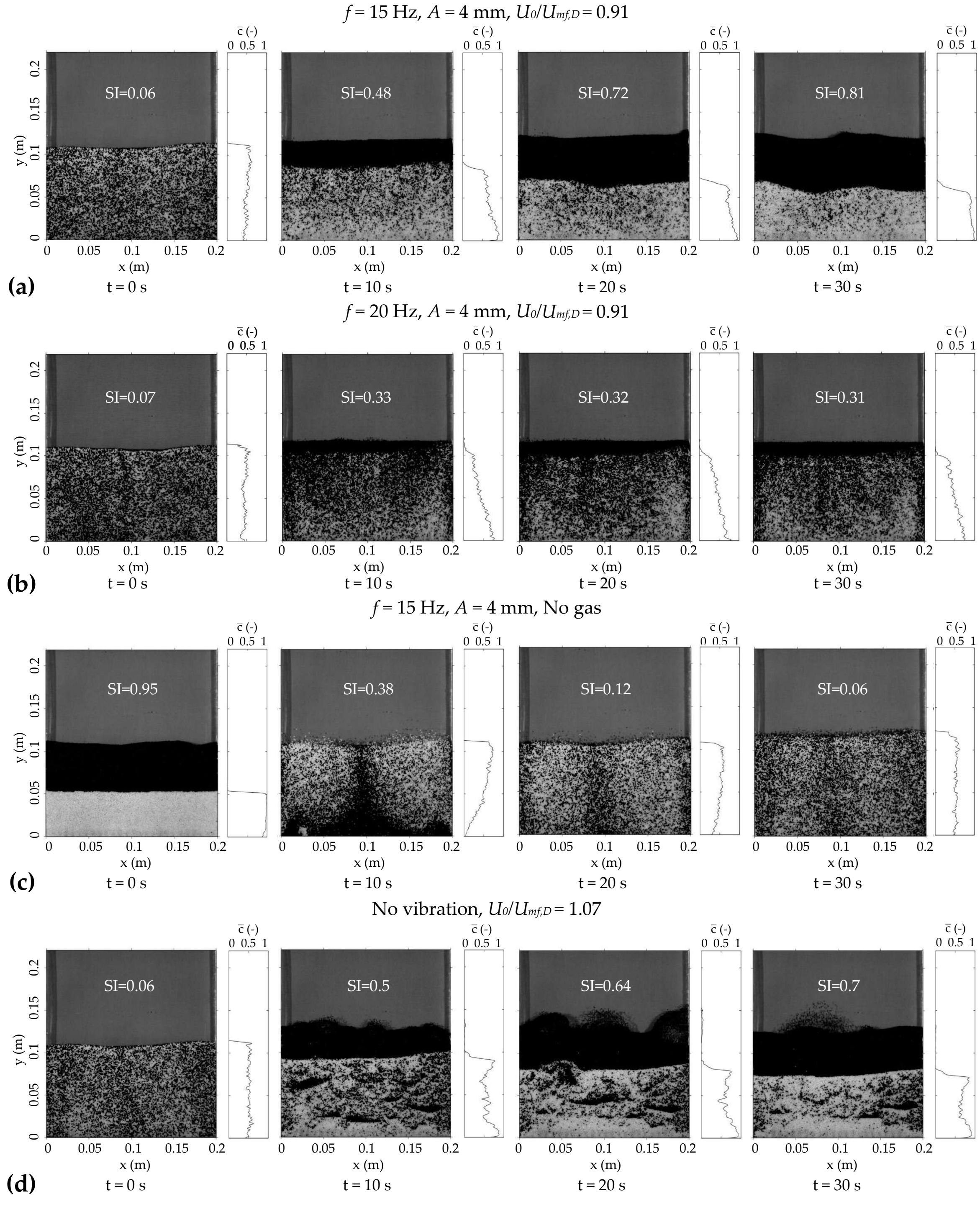

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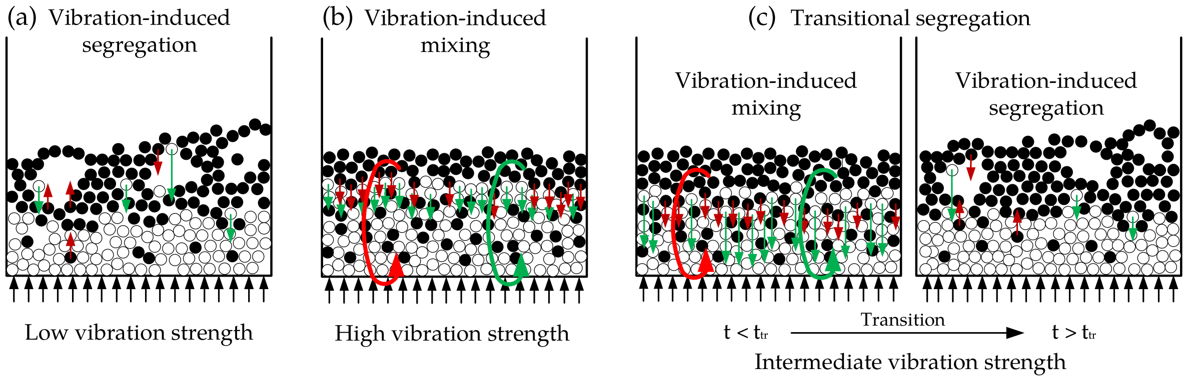

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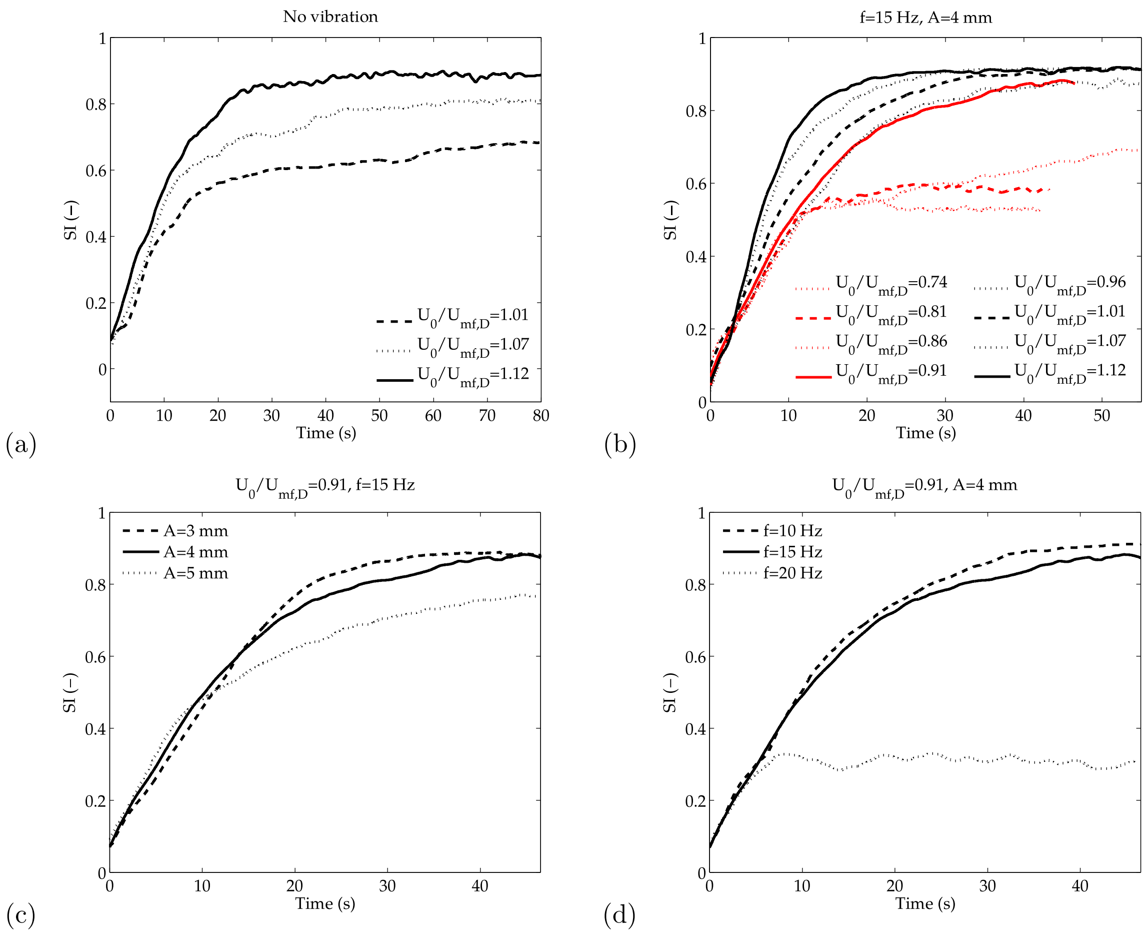

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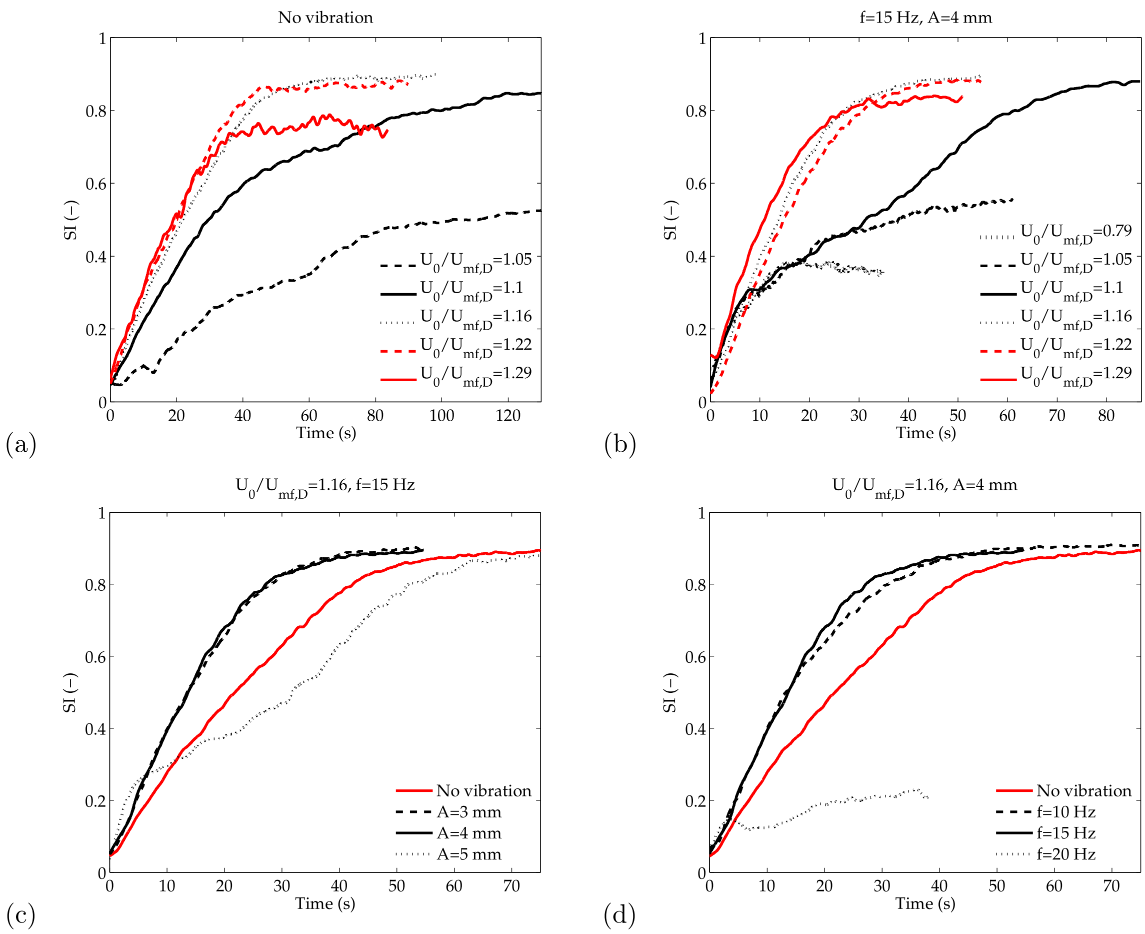

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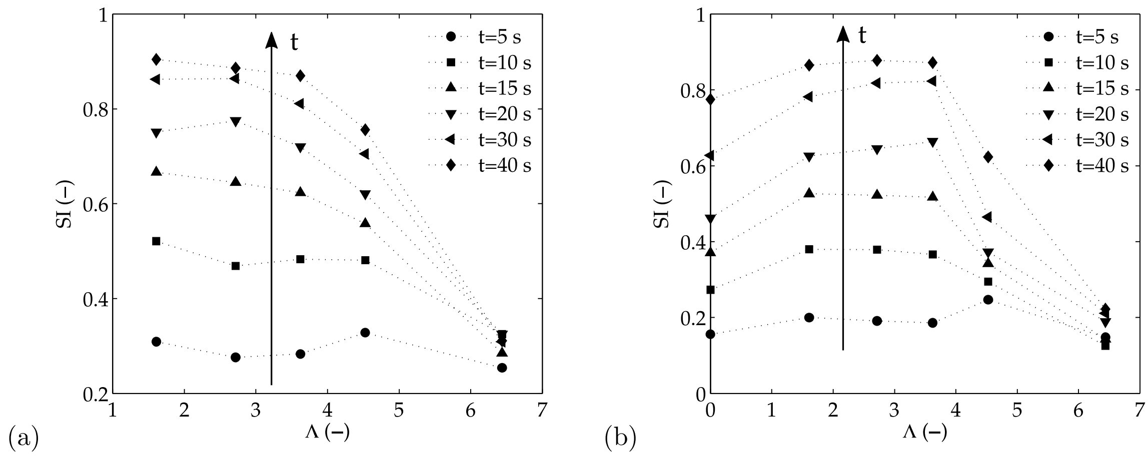

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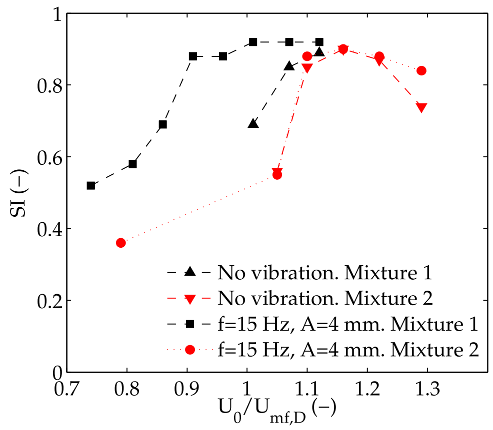
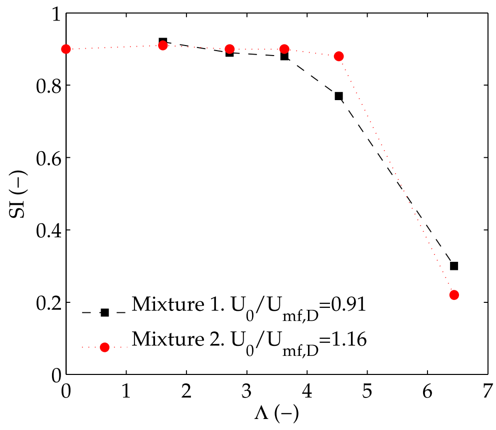


(a)



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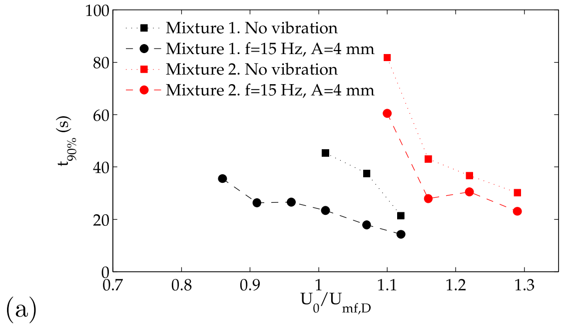

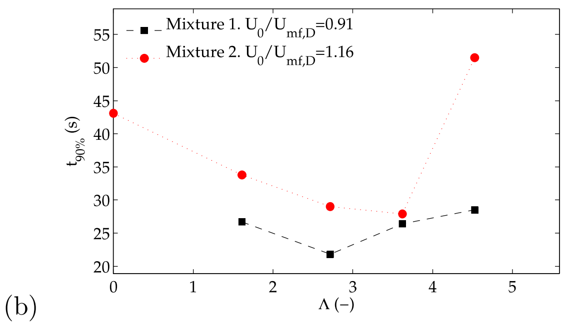

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Table 1: Properties of the mixtures of light (L) and dense (D) particles.

	$d_{p,L}$ (mm)	ρ_L (kg/m^3)	$U_{mf,L}$ (m/s)	$d_{p,D}$ (mm)	ρ_D (kg/m^3)	$U_{mf,D}$ (m/s)
Mixture 1	1−1.3	2500	0.63	1−1.2	6000	1.08
Mixture 2	1−1.3	2500	0.63	1−1.2	4100	0.85

Table 2: Experimental conditions. The bold numbers correspond to the reference cases.

f (Hz)	A (mm)	Λ (−)	**Mixture 1**	**Mixture 2**
			$U_0/U_{mf,D}$ (−)	$U_0/U_{mf,D}$ (−)
10	4	1.6	0.91	1.16
15	**4**	**3.6**	0.74, 0.81, 0.86, **0.91** 0.96, 1.01, 1.07, 1.12	0.79, 1.05, 1.1 **1.16**, 1.22, 1.29
20	4	6.4	0.91	1.16
15	3	2.7	0.91	1.16
15	5	4.5	0.91	1.16
No vibration			1.01, 1.07, 1.12	1.05, 1.1, 1.16, 1.22, 1.29