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MOTION OF A LARGE OBJECT IN A 2D BUBBLING FLUIDIZED BED

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ABSTRACT

The motion of a large object in a bubbling fluidized bed is experimentally studied using digital image analysis. A wide range of fluidized bed applications involves the motion of large objects within the bed, such objects being reactants, catalysts, agglomerates, etc.

The experiments were run in a 2D bubbling fluidized bed with glass spheres as bed material. The object motion is measured using tracking techniques, while independent measurements of the dense phase velocity (using PIV) and bubble velocity were carried out. The effect of the excess gas velocity on the object motion was also analyzed.

It is generally accepted that objects with densities in a range around the bed density will describe sinking-rising cycles throughout the whole bed, where the sinking motion is similar to that of the dense phase, and the rising motion is composed of a number of sudden jerks or jumps, as a result of the raising effect of passing bubbles. This work characterized the circulation patterns of an object with a density similar to that of the bed material, but much larger in size. A comparison between the object rising motion and the local bubble motion provided evidence for the study of the bubble ability to raise the object, depending on the bubble velocity and size. A comparison between the object sinking motion and the dense phase motion served to analyze the minor effect of buoyancy forces over the object sinking motion. Finally, the combined effects of the maximum attained depth and the number of jerks in the circulation time is studied, with some insight in the multiple-jerks phenomenon.

Keywords: Gas fluidization, Bubbling bed, Large object motion, Sinking and rising velocity, Circulation time.

1. INTRODUCTION

Bubbling Fluidized Beds (BFB) are widely used in industry (from pharmaceutical to energy conversion systems), with processes involving heat and mass transfer and chemical reaction. Examples include drying processes, thermal conversion of solid fuels, or coating of particles. A wide range of these applications involves the motion of large objects within the bed. The objects might be fuel particles, catalysts, reactants, agglomerates, etc. These objects will sink with the dense phase and rise with the bubbles, with the addition of buoyancy effects, which may or may not be significant. The

object motion patterns and its ability to move throughout the whole bed or stay in a restricted zone will have a paramount effect in the reaction time, the existence of hot or cold spots, the permanence of agglomerates, etc.

Several works have focused on the motion of an object within a BFB, and most of them are based on experimental analysis. These include experiments in 2D and 3D beds, using different measurement techniques. The first studies were reviewed by Kunii and Levenspiel (1). Rios et al. (2) studied the motion of large objects in 2D and 3D beds and discussed the sinking and rising processes. They also observed that the object was not always raised up to the freeboard by a single bubble, but was rather lifted small distances by a succession of passing bubbles, rising in a series of small jerks or jumps. Concerning the diving process, Lim and Agarwal (3), found that the diving velocity of a large object in a 2D bed was in good agreement with the Kunii and Levenspiel correlation for the velocity of the dense phase (for density ratios around 1), while Hoffmann et al. (4) showed that for large density ratios, a relative motion of sinking objects and dense phase existed and was linear with density. The rising velocity is related to the bubble velocity in a more complex way, due to the effect observed by Rios et al. (2) and to relative motions between bubble and object that are far more important than in the sinking process. Nienow et al. (5), Lim and Agarwal (3), and more recently Rees et al. (6) found the mean rising velocity to be roughly between 10% and 30% of the mean bubble velocity along the bed.

This work studies the motion in a 2D fluidized bed of large objects with a similar density than that of the bed material. The general patterns are presented and special attention is focused in characterizing the rising process and the incidence of multiple jerks. The influence of gas velocity is also analyzed.

2. EXPERIMENTAL SETUP

The experiments were carried out in a 2D column (50 cm width, 200 cm height, and 1 cm thickness). The bed material was glass spheres with a mean diameter of 700 μm and a density of 2,500 kg/m^3 (type B according to Geldart's classification). The bulk density of the fixed bed was measured to be 1,560 kg/m^3 , and 0.32 m/s is the minimum fluidization velocity, U_{mf} . The fixed bed height was 50 cm and the excess gas velocity U/U_{mf} was varied between 2 and 3 (2.5 being the nominal case). The object was a cylinder of 1,381 kg/m^3 density, 6.4 mm diameter, and 19.2 mm length. Therefore, the object-fixed bed density ratio was 0.88 and the object-bed material characteristic length ratio was 9.1. The distributor was designed to reduce the dead zones.

A standard camera was used to obtain the average motion patterns (1.6 fps) and the object velocity (30 fps), while the dense phase and bubble velocities were obtained using a high speed video camera (125 fps, *Redlake Motion pro X3*). Dense phase and bubbles were discriminated using a threshold of the greyscale map. For the PIV measurements of the dense phase velocity, the MatLab® MatPIV program developed by J. K. Sveen (<http://www.math.uio.no/%7E%7b%7djks/matpiv>) was employed. Image analysis, bubble tracking, and averaging techniques were also performed using

MatLab®. Object motion was observed in the darkness, as the object was coated with strontium aluminate, giving a green light emission.

Average measurements of the object position and velocity, and of bubbles and dense phase velocities were obtained. Averaged object position maps were obtained from 16,000 images, representing 10,000 seconds of the BFB activity. For the object velocity, 720 seconds and 21,600 images were recorded. Bubble and dense phase velocities were determined averaging 9,810 images, which in turn represents 78 seconds of the BFB activity.

3. EXPERIMENTAL RESULTS

Experimental results include the averaged motion patterns of the object, the study of the object average sinking and rising velocities and its comparison with average dense phase and bubble velocities. Furthermore, the characterization of the object circulation cycles (out and back to the freeboard) in the BFB in terms of number of jerks and circulation time was performed, and the average length that the object is carried up in one jerk (by a single passing bubble) was determined.

Motion patterns

Previous studies show that objects with different size than the bed material circulate throughout the whole bed for a wide range of object densities around that of the fluidized bed, while much denser objects fall straight to the bottom (and remain there) and much lighter ones are permanently kept near the freeboard. In this sense, a characterization of the relative frequency of the object presence in each position, and in particular the depth/height dependence, is of paramount importance to characterize the object circulation. **Fig. 1 a)** shows the probability to find the object for each depth (or height from the distributor), while in **Fig. 1 b)** the probability to find a particle that rises or sinks as a function of its position across the bed is plotted.

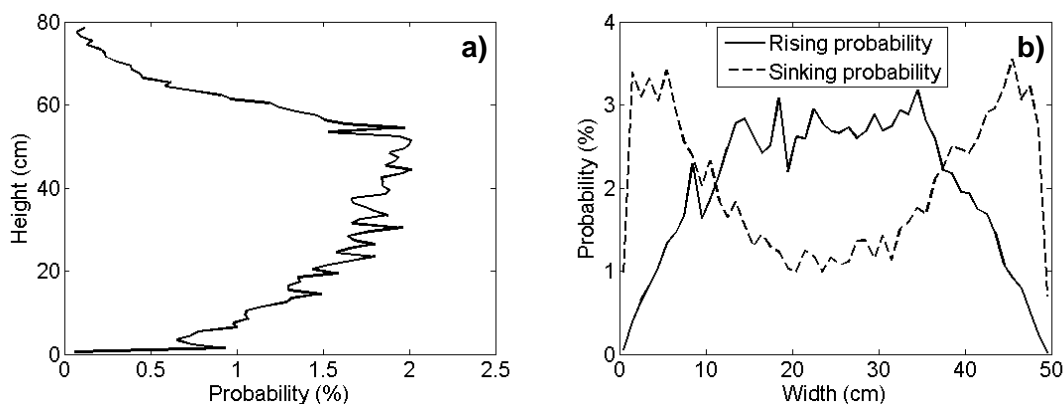


Fig. 1. Probability to find **a)** the object on a certain position as a function of the y-coordinate (height from the distributor), and **b)** a rising or a sinking object as a function of the x-coordinate of the bed (width). Nominal case ($U/U_{mf}=2.5$).

Fig. 1 a) reports that the distribution of the object in the upper 2/3 of the bed is fairly homogeneous (the fixed bed height was 50 cm), while in the region near the distributor (heights lower than 20 cm) the object is more seldom present. This may mean that there is a minimum bubble size necessary to assure a proper circulation of the dense phase (a minimum bubble size that is able to entrain sufficient dense phase material). When sizes are larger, the bubble motion provides quick circulation and a rather homogeneous mixing (at the top of the bed) and when they are smaller, the result is poor motion and depths difficult to attain (in the bottom zone).

Fig. 1 b) shows the preferred paths for the sinking and rising motions. The objects rise in the middle of the bed and sink in the sides. This is in accordance with the generally established bubble patterns and preferred paths in a 2D BFB. The variation of the excess gas velocity up to 3 or down to 2 has no significant influence on the graphs of **Fig. 1**, so it was not plotted.

Object sinking and rising velocities

Mean rising and sinking velocities for each depth were calculated as the averages of the upward or downward velocities experienced by the object at that depth. In a similar way, the mean bubble velocity and the dense phase mean velocity were calculated. The mean (for the whole bed) dense phase velocity and bubble velocity were in good agreement with the typical correlations of Kunii and Levenspiel (dense phase) and Darton (Darton (Z), bubble). The comparisons of the object sinking velocity with the dense phase velocity, and of the object rising velocity with the bubble velocity, are plotted in **Fig. 2**.

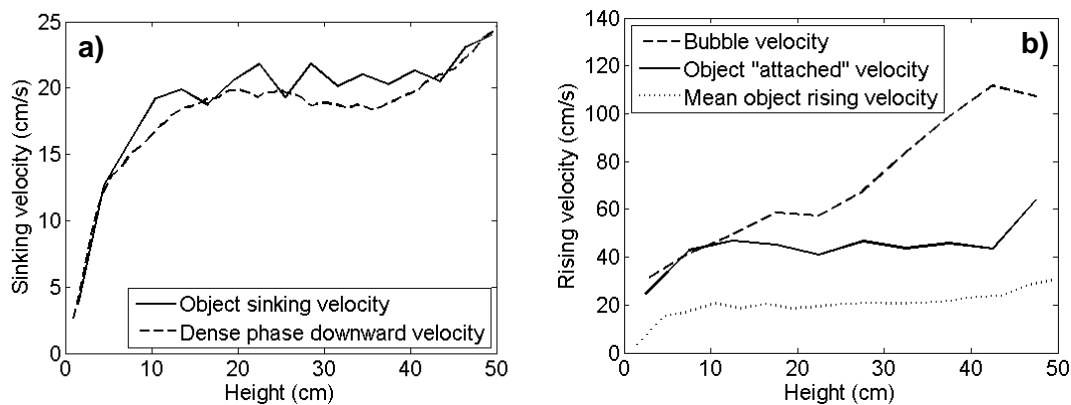


Fig. 2. Object mean velocity for the nominal case ($U/U_{mf}=2.5$), **a)** Object sinking velocity and dense phase velocity and **b)** object rising velocities and bubble velocity.

Fig. 2 a) shows that the mean object sinking velocity correlates well with the mean dense phase downward velocity for all depths/heights, a result that confirms the negligible effect of buoyancy forces for object–bed density ratios near 1. On the other hand, two main regions are evident in the graph, a lower region of 5 to 10 cm height where the velocities are rapidly increasing, and the rest of the bed, where they maintain

a similar value. This happens both for the object and for the dense phase. The initial region might be related with the existence of permanent jets and dead zones above the distributor, as studied by Rees et al. (8). The bubbles are then formed above this region, and they start to grow and to entrain dense phase further away. On the other hand, the stabilization of the mean velocities beyond that region is linked with the conservation of the bubble volume fraction. Finally, the larger values of the velocities near the fixed bed height are a result of the motion in the surroundings of erupting bubbles.

Fig. 2 b) compares the rising velocities of bubbles and objects. The bubble velocity increases almost linearly with height, while the object mean rising velocity (which, due to mass conservation, is very similar to the mean sinking velocity shown in the previous graph) stabilizes in much lower values. The mean velocities (for the whole bed) of both object and bubbles are related by a 30% ratio, as shown by previous authors, but it is shown that this can vary much, depending of the height of the experiments. In order to get a deeper insight of the rising process, the motion of the object throughout its rising path has been studied in more detail. The experimental evidence showed that when the object begins to move up, it takes some time to accelerate, due to competing bubble entrainment and inertia-viscous forces. Afterwards, if the object does not reach the freeboard, there is also a “detachment” time where it loses the trail of the bubble and is once more immersed in the dense phase. These “attachment” and “detachment” periods involve lower rising velocities that make the mean rising velocity smaller. Therefore, the third curve in **Fig. 2 b)** shows the rising mean velocity during the intermediate period where the object is supposedly “attached” to the bubble. If this velocity is compared with the mean bubble velocity, it shows that they are quite similar in the lower region of the bed (up to 15cm), but then the object velocity stabilizes while the bubble velocity continues to increase. This stabilization of the mean velocities suggests that for increasing bubble velocities, increasing viscous forces on the object may lead to more often object–bubble detachment.

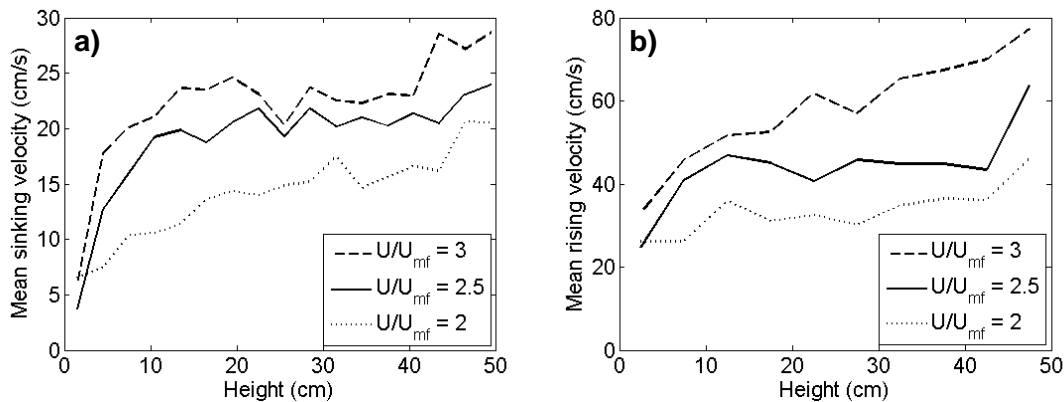


Fig. 3. Effect of the excess gas velocity on the object mean **a)** sinking velocity and **b)** rising velocity.

The effect of the excess gas on the object velocity is shown in **Fig. 3**. Excess gas velocity directly affects bubble size and thus bubble velocity and dense phase entrainment. **Fig. 3 a)** and **b)** shows its effect on the object sinking and rising velocity respectively. While the rest of the excess gas velocity effects shown in the graphs can be related with this effects, the stabilization of sinking and rising velocities is not so obvious in the $U/U_{mf}=2$ case (sinking motion) and in the $U/U_{mf}=3$ case (rising motion).

Jerk-jump behavior

Object sinking and rising velocities are especially important as they determine the circulation time of the object within the bed. **Fig. 4 a)** shows the experimental circulation times obtained for the object throughout the experiments (more than 1200 cycles) as a function of the maximum depth attained by the object. The dashed line, which roughly represents a minimum, is obtained by the integration of the sum of the inverses of the mean sinking and rising velocities shown in **Fig. 3**, a calculation that gives the circulation time for a one-jerk cycle of a particle moving at such mean velocities as a function of the maximum attained depth. It can be observed that the higher the depth the larger the time periods, but there is a huge dispersion of the data. This is in fact due to the incidence of multiple jerks or jumps during the rising process, associated with a series of passing bubbles that (each one of them) do not carry the object directly to the freeboard. **Fig. 4 b)** shows the same data arranged as a function of the number of jerks in each cycle. The graph shows that this has a stronger effect than attained depth in the circulation time (although, of course, a high number of jumps in the rising process is more prone to occur when a higher depth is attained).

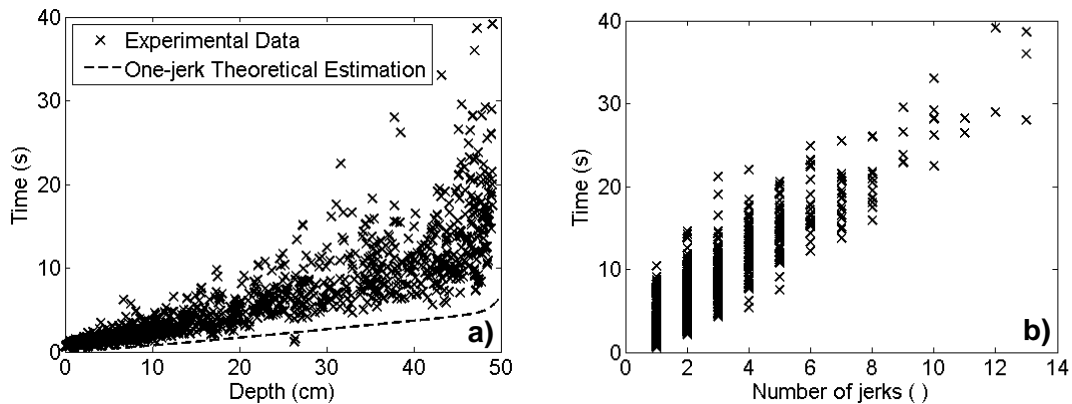


Fig. 4. Time periods for an object to rise back to the freeboard, **a)** as a function of the cycle maximum attained depth, **b)** as a function of the number of jerks employed to reach the freeboard. Nominal case ($U/U_{mf}=2.5$).

Therefore, the incidence of multiple-jerk cycles has to be studied in more detail. **Fig. 5** shows the probability of a number of jerks to occur in each cycle, and for various excess gas velocities. The graph shows an exponential decay between the number of jerks and their probability to occur, for the three cases. Furthermore, increasing the gas

velocity reduces the probability to find cycles with a high number of jerks, a result related with the increasing bubble volume fraction.

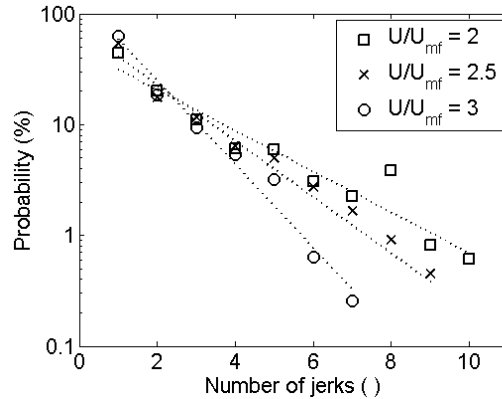


Fig. 5. Probability to find cycles with a determined number of jerks.

The number of jerks is defined by the height that the object can be raised. This might be a function of the bubble size and object size and mass, and thus it will vary with both the depth and the excess gas velocity. The mean height and standard deviation that the object is raised by a single bubble as a function of the depth is plotted in **Fig. 6 a)** for the nominal case. The dotted line represents the depth at which the object starts its upward motion, which is the maximum height that the object could be raised. The mean height increases with the depth (near to the dotted line, which means most of the rises end with the object in the freeboard), and then stabilizes in the lower half of the bed. This might suggest that the bubble diameter is not a relevant parameter, or that larger bubbles might easily lose an object, and thus the mean value decreases. This behavior was similar when the excess gas velocity was varied, thus only the variation of the mean lifting height from the distributor (maximum depth) with the excess gas velocity is presented in **Fig. 6 b)**, in which a slight increase with the excess gas velocity is observed.

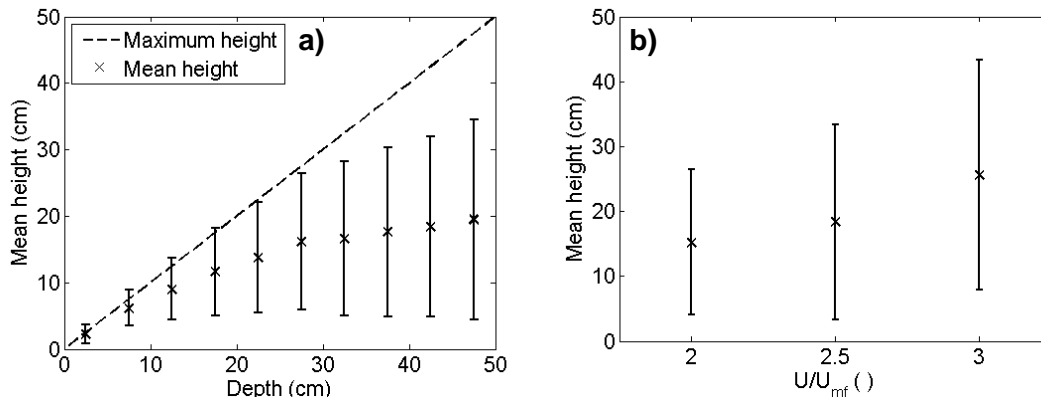


Fig. 6. Mean height that the object is raised in one jerk, **a)** as a function of the depth (nominal case $U/U_{mf}=2.5$), **b)** from the distributor, as a function of the excess gas velocity.

4. CONCLUSIONS

The motion of a large object within a 2D bubbling fluidized bed was studied, considering the motion patterns, the object sinking and rising velocity, and the multiple-jerks behavior of the rising path. The effect of the excess gas velocity on the main parameters of the motion was also analyzed.

The object (larger and with a similar density than the bed material) had a proper circulation through the whole bed, sinking at the sides of the bed and rising in the middle, where bubbles are more probably found. The sinking motion was found to be affected only by the dense phase motion, with a negligible effect of buoyancy forces. An initial zone appears, probably linked to the bubble formation region after which the sinking velocity remains constant throughout the bed. The rising motion is affected by bubbles, although there is a large deviation between the object and the bubble velocity, and also on the shape of both curves.

The time periods of the object depend on the maximum depth attained by the object, but the number of jerks needed for the object to go back to the freeboard has a paramount influence on this parameter. The relation between the number of jerks and the time periods was found to be linear, with a low dispersion of the data due to the maximum depth attained in each case. The probability to find cycles with a determined number of jerks has an inverse exponential relation with the number of jerks. The exponent increases with increasing excess gas velocity.

The mean height that an object is raised by a passing bubble defines the number of jerks. The mean height increases with the depth until a certain value, after which it stabilizes. This may mean that almost all the bubbles have a similar capability of raising an object.

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