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2013

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L.M. Garcia-Gutierrez

*Carlos III University of Madrid, Spain*

A. Soria-Verdugo

*Carlos III University of Madrid, Spain*

C. Marugán-Cruz

*Carlos III University of Madrid, Spain*

U. Ruiz-Rivas

*Carlos III University of Madrid, Spain*

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### Recommended Citation

L.M. Garcia-Gutierrez, A. Soria-Verdugo, C. Marugán-Cruz, and U. Ruiz-Rivas, "Object Motion in the Freeboard of a Bubbling Fluidized Bed" in "The 14th International Conference on Fluidization – From Fundamentals to Products", J.A.M. Kuipers, Eindhoven University of Technology R.F. Mudde, Delft University of Technology J.R. van Ommen, Delft University of Technology N.G. Deen, Eindhoven University of Technology Eds, ECI Symposium Series, (2013). [http://dc.engconfintl.org/fluidization\\_xiv/62](http://dc.engconfintl.org/fluidization_xiv/62)

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# OBJECT MOTION IN THE FREEBOARD OF A BUBBLING FLUIDIZED BED

L.M. Garcia-Gutierrez\*, A. Soria-Verdugo, C. Marugán-Cruz and U. Ruiz-Rivas  
*Energy Systems Engineering Group, Department of Thermal and Fluids  
Engineering, Carlos III University of Madrid.  
Avda. Universidad 20, 28911 Leganés Madrid, (Spain).*

*\*corresponding author: lmgarcia@ing.uc3m.es. Tel: +34916248884. Fax:  
+34916249430.*

## ABSTRACT

The motion of a large object in the freeboard of a 2D bubbling fluidized bed was studied, and a simple kinematic model was developed to estimate key parameters such as the lateral dispersion coefficient and the time of flight of the object in the freeboard. The experimental data were obtained using a technique, capable of tracking at the same time the object, the dense phase and the bubbles. The model was established considering that the object motion in the freeboard is only affected by gravitational forces; in the absence of dense phase interactions and with negligible air drag forces due to the large volume of the object. This results in a parabolic motion of the object defined by its initial velocity (ejection velocity, modulus and polar angle) and the gravity.

## INTRODUCTION

Many applications in fluidized beds involve the motion of objects inside the bed. These objects may be fuel particles, catalyzers or agglomerates. For a proper performance of the bed a high mixing rate is required. The vertical mixing rate in fluidized beds is much higher than the lateral mixing rate (Ito et al., (1)), therefore the lateral dispersion coefficient is a key parameter in these applications.

Several studies have measured the lateral dispersion coefficient in both 3D and 2D beds. In 3D beds, the coefficient has been estimated indirectly using defluidized bed sieving (Xiang et al., (2)) and residence time distributions (Bi et al., (3)). On the other hand, Olsson et al., (4) calculated the lateral dispersion coefficient based on direct estimations using particle tracking of objects in the freeboard. In 2D beds different measurement techniques have been employed, including solids concentration sampling (Salam et al., (5), Xiao et al., (6), Schlichthaerle and Werther, (7)) and tracking techniques (Pallarès and Johnsson, (8), Pallarès et al., (9)). Olsson et al., (4) reviewed the results of the lateral dispersion coefficient calculated in previous works. Their work states a general lack of experimental evidence and a predominance of 2D experiments over 3D experiments. The results in 2D beds can only be extrapolated qualitatively to 3D beds, but they cover a wider range of bed configurations (dimensionless gas velocities, bed heights, bed materials, etc.) than the seldom available 3D experiments. The data showed that the dimensionless gas velocity ( $U/U_{mf}$ ) is the most relevant parameter. For  $U/U_{mf}$  between 1 and 30 the dispersion coefficients varied in the range  $10^{-4}$  -  $10^{-1}$  m<sup>2</sup>/s. There is a high scattering for both 3D and 2D configurations, without a marked difference between 2D and 3D data. For

example, for  $U/U_{mf}$  values around 3, 6 or 13, the values obtained by different authors differ roughly an order of magnitude (between  $10^{-3}$  and  $10^{-2}$  m<sup>2</sup>/s for  $U/U_{mf}=6$ ).

In the present work, the lateral dispersion coefficient is obtained from the study of the object trajectories in the freeboard (thus not considering here the dispersion produced by lateral motion inside the dense bed). The literature on ejection mechanisms in fluidized beds has been studied. Several works (Peters and Prybylowski (10), Fung and Hamdullahpur, (11), Almendros et al. (12)) studied the ejection velocity of the dense phase, but to the authors knowledge, there is no work available concerning the ejection velocity of a large object. For dense phase particles, the models of the different authors differ. Peters and Prybylowski (10) assumed a constant radial velocity with a value of about twice the bubble velocity; on the other hand, Fung and Hamdullahpur, (11) and Almendros et al. (12) proposed models where the velocity varied as functions of the polar angle.

A tracking technique has been developed to follow a circular object immersed in a 2D bubbling fluidized bed. A 2D bed was selected as a first step, since the object path can be analyzed entirely, and a direct measurement of the lateral dispersion coefficient can be carried out, but the extrapolation of the results to 3D beds is not straightforward, as explained before. From the tracking technique data, the ejection of the object by the bubbles has been analyzed and compared with a parabolic motion. The time of flight of the object in the parabolic motion and the modulus and polar angle of the (initial) ejection velocity were determined for each ejection. Using this data, a model was developed in order to extrapolate the results for different configurations (different dimensionless gas velocities and bed heights). Finally, the lateral dispersion coefficient of the object at the freeboard was determined experimentally and estimated using a kinematic model based on the dimensionless gas velocity and bed height.

## EXPERIMENTAL SETUP

The tests were carried out in a 2D bubbling fluidized bed with a height,  $H$ , of 2m, a width,  $W$ , of 0.5m and a thickness,  $T$ , of 0.005m. The bed material used was glass spheres (Ballotini particles) with a diameter between 600-800  $\mu$ m. The dense phase particle density was 2500 kg/m<sup>3</sup>, corresponding to Geldart's B classification. The bulk density of the bed was measured to be 1560 kg/m<sup>3</sup> and the minimum fluidization velocity,  $U_{mf}$  was 0.49 m/s. The dimensionless gas velocity during the experiments,  $U/U_{mf}$  was set to 2 and 2.5 and two different fixed bed heights,  $h_b$ , were used, of 0.3m and 0.5m, giving a total of four different experimental configurations. The object used in the tests had a disc shape with a diameter of 0.02m and a thickness of 0.003m. The density of the object was measured to be 1200 kg/m<sup>3</sup> and thus the behavior of the object in the bed was flotsam.

A tracking technique was developed to characterize the motion of the object in the bed, visualizing the dense phase, the bubbles and the object at the same time using Digital Image Analysis. The acquisition system consisted of a high speed video camera (125 fps, Redlake Motion pro X3 4Gb) and an illuminating system. The illumination was carried out with four spotlights of 650W, giving a homogeneous illumination of the whole bed. For each configuration, 65420

images were taken that correspond to around 524s. A threshold was used to characterize the position of the object in all the images, obtaining the velocity of the object at each instant. On the other hand, the dense phase and the bubbles were discriminated using also a threshold of the grayscale map. The Digital Image Analysis was performed using a MatLab® algorithm.

## RESULTS AND DISCUSSION

The behavior of the object in the freeboard was analyzed. The object moved throughout the bed and in the freeboard, in a region roughly defined between the distributor and twice the bed height. The dynamics of an object immersed in a fluidized bed shows the incidence of interactions with adjacent bed particles, gravitational forces and drag forces. However, in the freeboard particle interactions diminish and only the gravitational and drag forces are relevant. Furthermore, in the case of a large object the drag force becomes negligible ( $0.056 \text{ m/s}^2$  against  $9.81 \text{ m/s}^2$  in our case, for  $U/U_{mf}=2.5$ ). Thus the object should follow a parabolic motion in the freeboard. Such a motion has been studied and characterized for all the experimental cases. Nevertheless, the actual behavior of the object in the freeboard may sometimes differ from the parabolic motion. Other forces can appear, such as interactions with dense phase particles in the corolla of an erupting bubble, collisions to the width limits of the fluidized bed or interactions with the 2D bed walls, among others. In this work we have tried to characterize the object motion in the freeboard subjected only to the parabolic motion (in order to separate possible 2D effects), so the rest of the cases are disregarded (collisions with the width limits will be included, by focusing on the vertical motion of the object). Therefore several conditions were established in the procedure to decide at which intervals of each recorded test the object was following an ejection trajectory in the freeboard and whether such an ejection could be considered or not a parabolic motion.

First, the data obtained using the tracking technique were processed and the vertical position as a function of time was extracted. Then, the local peaks of the vertical position were selected. Those peaks were considered to relate to potential maxima of an ejection trajectory when the peak height was larger than  $1.3 \cdot h_b$  (thus removing peaks occurring inside the bed) and when similar peaks did not appear sooner than 0.25 seconds (thus excluding vibrating motions on the bed surface). Once the event of an ejection is revealed in such a way, its beginning and end was determined. This was performed looking at a consistent increment of the vertical velocity at instants previous to the peak, and a consistent decrement of the vertical velocity at instants following to the peak. When such behaviour was not observed in at least two consecutive instants (one isolated datum was not considered sufficient due to the experimental accuracy), the ejection was considered to have finished (or not yet begun). Finally, the parabolic trajectory of the obtained events was tested using a parabolic fitting of the data, and those fittings that presented a coefficient of determination  $R^2$  (a coefficient that describes how well a regression line fits a set of data) larger than 0.997 were accepted. Only those trajectories that consisted of at least five previous and ten following instants were considered in order to exclude results based in insufficient data (15 points represent 0.12 seconds). The difference between the figures for previous and following instants relies on the actual shape of the obtained trajectories, showing far more data after the maximum than

before it. Figure 1 shows an example of a parabolic motion of the object for the experimental case of 0.5m height and  $2.5 U/U_{mf}$ . The cross marks represent the experimental vertical position of the object. The solid line represents the parabolic fitting of the experimental data at the beginning and end of the parabolic path are marked with circles.

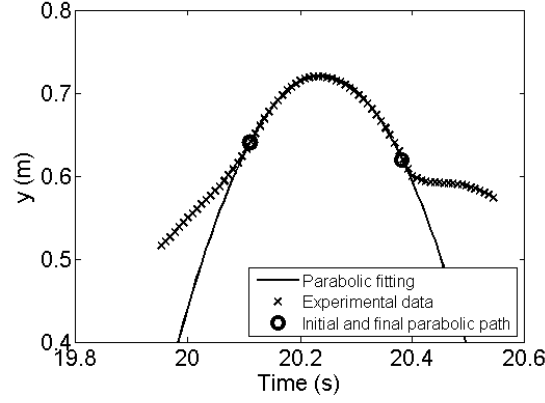


Figure 1. Parabolic fitting for the vertical position in a particular object path.

### Parabolic motion modeling

The time of flight (the time between the instants of the initial and final object position in the freeboard) and the lateral displacement of an object following a parabolic path, where the only force is the gravitational force, can be expressed by Eq. (1) and Eq. (2) respectively.

$$t_f = \frac{V_{oy} + \sqrt{V_{oy}^2 + 2 \cdot g \cdot \Delta y}}{g} \quad (1)$$

$$\Delta x = V_{ox} \cdot t_f \quad (2)$$

where  $g$  is the acceleration of gravity,  $V_{ox}$  and  $V_{oy}$  are the horizontal and vertical components of the initial object velocity, and  $\Delta y$  is the vertical displacement between the final and the initial position. These last three variables were obtained experimentally.  $V_{oy}$  was integrated from the total parabolic trajectory, whereas  $V_{ox}$  was obtained as the velocity at the initial instant, to include parabolic trajectories that interact with the width limits of the bed. The results were compared with the bubble velocity calculated using the correlation of Davidson and Harrison (13) (Eq. 3) and Shen correlation (Eq. 4) to calculate the diameter of the bubble in a 2D bed (Shen et al., (14)).

$$U_B = U - U_{mf} + \phi \sqrt{g D_B} \quad (3)$$

$$D_B = \left[ \left( \frac{8 \cdot 2^{3/4} - 1}{\lambda} \right) U - U_{mf} \left( h + \frac{\lambda}{\pi \cdot 2^{3/4} - 1} \frac{A_0}{T} \right) \right]^{2/3} g^{-1/3} \quad (4)$$

Figure 2 shows the initial vertical velocity of the object at the instant of its ejection against the polar angle of the ejection (the angle of the velocity vector relative to the vertical coordinate). A polynomial fitting is included and compared with the vertical velocity considering a velocity modulus equal to the bubble velocity for all polar angles. This shows a good compromise. This result is not in agreement with any of the available models of particle ejection presented in the introduction, showing that large objects follow rather different behaviors. Note also that the polar angle of the object ejection varied between  $0^\circ$  and  $50^\circ$ . No parabolic motion was observed showing an initial ejection polar angle larger than  $50^\circ$ .

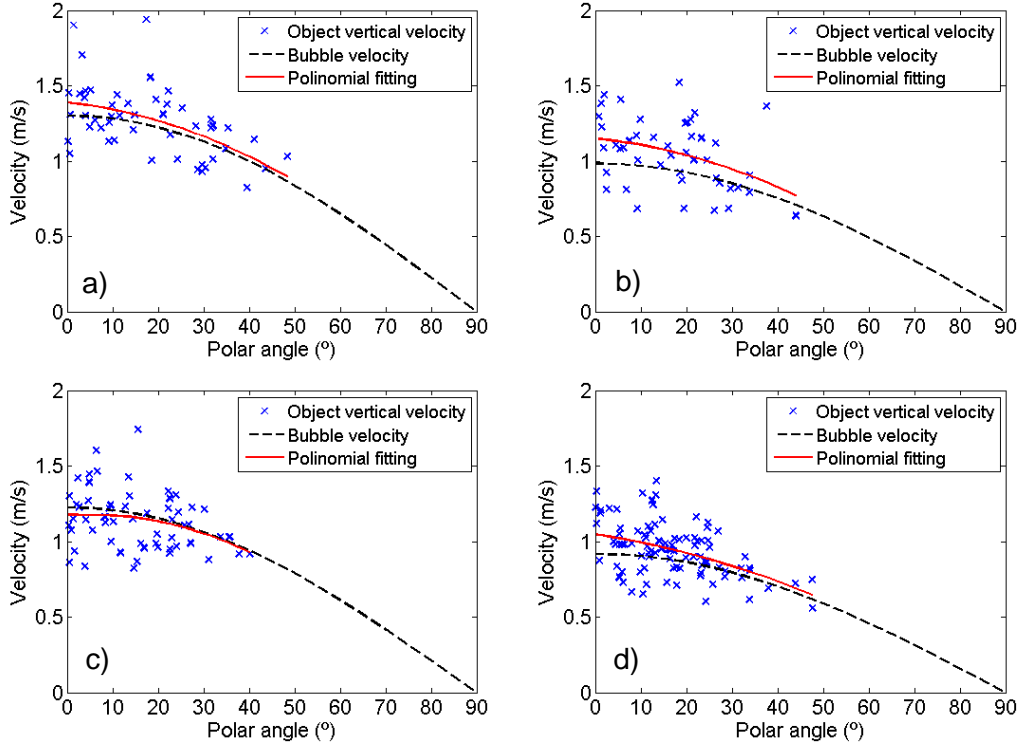


Figure 2. Vertical ejection velocity as a function of polar ejection angle for different  $H$  and  $U/U_{mf}$ : a) 0.5m, 2.5; b) 0.5m, 2; c) 0.3m, 2.5 and d) 0.3m, 2.

In order to obtain results for the time of flight and lateral motion of Eqs (1) and (2), the mean ejection velocities should be obtained. Thus the mean vertical velocity of the object at the instant of its ejection can be expressed as a function of the bubble velocity and the average of the distribution of ejection polar angle cosines (Eq. 5). On the other hand, the mean horizontal velocity of the object at the instant of its ejection was expressed as a function of the bubble velocity and of the distribution of ejection polar angle sinus (Eq. 6).

$$V_{oy} = U_B \cdot \overline{\cos \theta} \quad (5)$$

$$V_{ox} = U_B \cdot \overline{\sin \theta} \quad (6)$$

where  $\theta$  is the polar angle. Finally, some information about the vertical coordinate difference between the final and the initial position  $\Delta y$  should be obtained. In a first approximation, it seems reasonable to consider  $\Delta y = 0$  as a general model.

Nevertheless, the experiments show that the term tends to have a positive value. This can be explained as the ejection is often initiated at the corolla of the bubble, while the final position is over the bed surface and after the bubble has left the bed. Therefore, a simple model considering deviations of around the bubble diameter ( $\Delta y = D_B$ ) can also be considered. Both hypotheses are used in the following calculations.

### Time of flight and lateral dispersion coefficient

From the previous equations (1) to (6) the time of the flight and the lateral displacement of the object can be calculated as a function of the bubble velocity and the ejection polar angle (Eq. 7 and Eq. 8). Also, the lateral dispersion coefficient can be obtained using Eq. (9)

$$t_f = \frac{U_B \cdot \overline{\cos \theta} + \sqrt{U_B \cdot \overline{\cos \theta}^2 + 2 \cdot g \cdot \Delta y}}{g} \quad (7)$$

$$\Delta x = U_B \cdot \overline{\sin \theta} \cdot t_f \quad (8)$$

$$D_x = \frac{\Delta x^2}{2 \cdot t_f} \quad (9)$$

The results of this model are plotted in Figure 3 together with the experimental data obtained, as a function of the bubble velocity. The experimental data is described by the mean value for each configuration. Figure 3a) shows the time of flight of the object for the four different configurations. The solid line and the dashed line represent the two hypothesis concerning  $\Delta y$  that have been previously discussed. Note that the mean values of the experimental data hide large deviations (around  $\pm 0.05$ s). These results show some differences between the cases with different  $U/U_{mf}$ . The theoretical time calculated using the hypothesis of  $\Delta y = D_B$  seems to better represent the mean values of the two cases with  $U/U_{mf} = 2$ , while the two cases with  $U/U_{mf} = 2.5$  lay between the theoretical time calculated using the hypothesis of  $\Delta y = 0$  and that calculated using the hypothesis of  $\Delta y = D_B$ . This is due to a similar effect in the experimental  $\Delta y$  observed in the different cases that should be further explored. Except for these observations, the simple kinetic model shows a good agreement with the results.

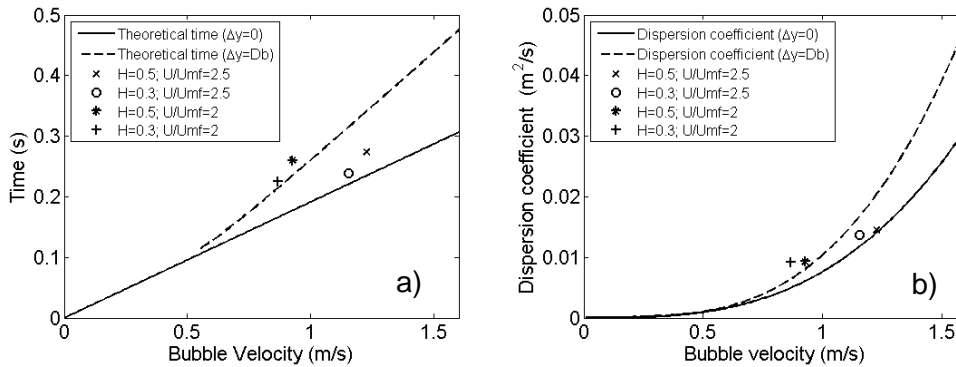


Figure 3. Time of flight (a) and lateral dispersion coefficient (b).

On the other hand, Figure 3b) shows the results for the lateral dispersion coefficient. The experimental data statistics were obtained after excluding from the calculation the paths that reached the width limits of the bed (between 25 and 30% of the cases studied). These tend to underestimate the mean, but the effect has been studied preliminary and it is not large. The theoretical models show a reasonable agreement with the experimental values. Again, the results obtained for the cases of  $U/U_{mf}=2$  fit better with the hypothesis of  $\Delta y=D_B$ , while the mean values of cases  $U/U_{mf}=2.5$  are close to the hypothesis of  $\Delta y=0$ .

## CONCLUSIONS

The motion of a large object in the freeboard of the bed was studied to characterize the lateral dispersion and time of flight of the object. An experimental study was carried out in a 2D bed for different configurations of gas velocity and bed heights; and a kinematic model was developed to characterize the ejection trajectory of the object. The motion of the object in the freeboard is defined by a parabolic motion driven by gravity and the initial ejection velocity.

The experimental distribution of initial velocities (modulus and polar angle) showed that the polar angle of ejection is always lower than  $50^\circ$ , and that the velocity modulus is independent of the polar angle of ejection and with a value similar to the bubble velocity. Using these parameters to model the ejections, the time of flight and lateral dispersion could be estimated. Both the time of flight and the lateral dispersion coefficient estimations show a good agreement with the experimental data. Further extension of the model to different configurations, including 3D data, is needed.

## ACKNOWLEDGEMENT

This work has been partially supported by the National Energy Program of Spanish Government (DPI2009-10518 MICINN) and the Madrid Community (CARDENER-CM S2009ENE-1660).

## NOTATION

$A_O$	Area of the distributor per number of orifices [m <sup>2</sup> ]
$D_B$	Bubble diameter [m]
$D_x$	Lateral dispersion coefficient [m <sup>2</sup> /s]
$g$	Gravity [m/s <sup>2</sup> ]
$h$	Height over the distributor [m]
$h_b$	Fixed bed height [m]
$H$	Height of the experimental facility [m]
$T$	Bed thickness [m]
$t_f$	Time of flight [s]
$U$	Superficial gas velocity [m/s]
$U_B$	Bubble velocity [m/s]
$U_{mf}$	Minimum fluidization velocity [m/s]
$V_{ox}$	Horizontal initial object velocity [m/s]
$V_{oy}$	Vertical initial object velocity [m/s]
$W$	Width of the experimental facility [m]
$\Delta x$	Lateral displacement [m]
$\Delta y$	Vertical displacement [m]



$\lambda$	Constant determined experimentally [-]
$\phi$	Constant determined experimentally [-]
$\theta$	Polar angle [rad]

## REFERENCES

1. Ito, O., Kawabe, R., Miyamoto, T., Orita, H., Mizumoto, M., Miyadera, H., Tomuro, J., Hokari, N., Iwase, T., 1999. Direct measurement of particle motion in a large- scale FBC boiler model, International Conference on Fluidized Bed Combustion, p. 217.
2. Xiang, Q., Huang, G., Ni, M., Cen, K., Tao, T., 1987. Lateral dispersion of large coal particles in an industrial scale fluidised bed combustor, 9th International Conference on Fluidized Bed Combustion, pp. 546–553.
3. Bi, J., Yang, G., Kojima, T., 1995. Lateral mixing of coarse particles in fluidized beds of fine particles. Chem. Eng. Res. Des. 73, 162–167.
4. Olsson, J., Pallarès, D., Johnsson, F., 2012. Lateral fuel dispersion in a large-scale bubbling fluidized bed. Chem. Eng. Sci. 74, 148-159.
5. Salam, T.F., Ren, Y., Gibbs, B.M., 1987. Lateral solid and thermal dispersion in fluidized bed combustors, International conference on Fluidized Bed Combustion, pp. 541–545.
6. Xiao, P., Yan, G., Wang, D., 1998. Investigation on horizontal mixing of particles in dense bed in circulating fluidized bed (CFB). J. Therm. Sci. 7, 78–84.
7. Schlichthaerle, P., Werther, J., 2001. Solids mixing in the bottom zone of a circulating fluidized bed. Powder Technol. 120, 21–33.
8. Pallarès, D., Johnsson, F., 2006. A novel technique for particle tracking in cold 2-dimensional fluidized beds simulating fuel dispersion. Chem. Eng. Sci. 61, 2710–2720.
9. Pallarès, D., Díez, P., Johnsson, F., 2007. Experimental Analysis of Fuel Mixing Patterns in a Fluidized bed, 12<sup>th</sup> Int. Conf. on Fluidization, Vancouver, Canada, p. 929–936.
10. Peters, M. H. and Prybylowski D. L., 1983. Particle above the surface of a fluidized bed: Multiparticle Effects. AIChE Symposium Series, 79, pp. 83-86.
11. Fung, A. S. and Hamdullahpur, F., 1993. A gas on particle flow model in the freeboard of a fluidized bed based on bubble coalescence. Powder Technol, 74, pp. 121-133.
12. Almendros-Ibáñez, J.A., Sobrino, C., de Vega, M., Santana, D., 2006. A new model for ejected particle velocity from erupting bubbles in 2-D fluidized beds. Chemical Eng. Sci., 61, 5981-599.
13. Davidson J.F., Harrison D., 1963. Fluidised particles, 1st ed. Cambridge University Press, Cambridge.
14. Shen L., Johnsson F., Leckner B., 2004. Digital image analysis of hydrodynamics two-dimensional bubbling fluidized beds. Chemical Engineering Science 59, 2607-2617.