2007 ECI Conference on The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering
Vancouver, Canada
Editors: Franco Berruti, The University of Western Ontario, London, Canada
Xiaotao (Tony) Bi, The University of British Columbia, Vancouver, Canada
Todd Pugsley, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Year 2007 *Paper* 19

Throughflow Velocity Crossing the Dome of Erupting Bubbles in 2-D Fluidized Beds

J. A. Almendros-Ibáñez[*] C. Sobrino[†] S. Sánchez-Delgado[‡]
D. Santana[**] M. de Vega[††] U. Ruiz-Rivas[‡‡]

[*]Universidad Carlos III de Madrid
[†]Universidad Carlos III de Madrid
[‡]Universidad Carlos III de Madrid
[**]Universidad Carlos III de Madrid
[††]Universidad Carlos III de Madrid
[‡‡]Universidad Carlos III de Madrid

Throughflow Velocity Crossing the Dome of Erupting Bubbles in 2-D Fluidized Beds

Abstract

A new non-intrusive method for measuring the throughflow velocity crossing the dome of erupting bubbles in freely bubbling 2-D fluidized beds is presented. Using a high speed video-camera, the dome acceleration, drag force and throughflow velocity profiles are obtained for different experiments, varying the superficial gas velocity. The acceleration profiles show greater values in the dome zone where the gravity component is negligible. The drag force and the throughflow velocity profiles show a uniform value in the central region of the dome (40 deg < < 140 deg) and the total throughflow increases with the superficial gas velocity.

THROUGHFLOW VELOCITY CROSSING THE DOME OF ERUPTING BUBBLES IN 2-D FLUIDIZED BEDS

J.A. Almendros-Ibáñez*, C. Sobrino, S. Sánchez-Delgado, D. Santana, M. de Vega and U. Ruiz-Rivas
Universidad Carlos III de Madrid, Dpto. de Ingeniería Térmica y de Fluidos
Avda. De la Universidad 30, 28911, Leganés, Madrid, Spain
*Corresponding author: T: +34916248884; F: +34916249430;
E: jalmendr@ing.uc3m.es

ABSTRACT

A new method for measuring the throughflow velocity crossing the dome of erupting bubbles in freely bubbling 2-D fluidized beds is presented. Using a high speed video-camera, the dome acceleration, drag force and throughflow velocity profiles are obtained for different experiments, varying the superficial gas velocity. The acceleration profiles show greater values in the dome zone where the gravity component is negligible. The drag force and the throughflow velocity profiles show a uniform value in the central region of the dome (40 deg < θ < 140 deg) and the total throughflow increases with the superficial gas velocity.

INTRODUCTION

In bubbling fluidized beds, bubbles generate a preferential path for the fluidizing air due to a more favourable pressure gradient through the bubble. Therefore, the throughflow crosses the bed, until it reaches the bed surface, following these preferential paths opened by the bubbles and does not react with the solid phase (1). When erupting, these bubbles form cavities connecting to the freeboard and the throughflow crossing them is proportional to the depth of the cavity (2). This flow through the erupting bubbles projects into the freeboard the dome's particles in the bubble eruption process. This mechanism together with the projection of particles from the wake are the main causes of the elutriation and/or entrainment.

Levy et al. (3), based on Davidson's model and including the dynamic of the free surface of the bed, developed a simple model for computing the throughflow velocity (U_r) in isolated spherical bubbles erupting at the bed surface. Their results show a core region where U_r is greater than the value at infinity and an exterior annular region where U_r is lower than the value far away. Nevertheless, their model is limited to the case of constant porosity through the dome during the bubble eruption. Later on, Gera and Gautam ((4) , (5) and (6)) extended the work of Levy et al. including the variation of the porosity through the dome. They also analyzed the effect of bubble aspect ratio and bubble coalescence on the throughflow velocity.

The effect of the depth of the erupting bubble was discussed by Levy et al. (3), who show that U_r increases with the aspect ratio, and by Glicksman and Yule (2) who obtained a general expression for the flow through cavities at the free surface as function of the cavity depth, corroborating the increase of the throughflow with the bubble aspect ratio. Hailu et al. (7) directly measured the throughflow velocity of the gas in 2-D injected bubbles using a back-scattering type Laser Doppler Velocimeter. They showed that this velocity increases with both bubble diameter and distance above the distributor until the bubble erupts at the bed surface.

In this work the throughflow crossing the dome of erupting bubbles in a freely bubbling 2-D fluidized bed was estimated by a force balance in the dome. We used a high speed video-camera for measuring the particle acceleration. In the following section we briefly describe the experimental set up, then we explain the method followed in order to obtain the throughflow and in the last two sections we show the experimental results obtained and summarize the main conclusions of the work.

EXPERIMENTAL SET-UP

The experimental measurements where carried out in a 2-D bubbling fluidized bed, similar to the one used by Almendros-Ibáñez et al (8). The bed (110 cm width x 60 cm height x 0.5 cm thickness) was constructed with two glass walls in order to allow us to take photographs of the bed interior during the experiments. The distributor was formed by one line of 110 holes of 1 mm diameter, resulting in a 1.43 % open-area ratio. The fluidized particles were glass spheres with a diameter ranging between 300 and 400 μm and a density ρ_p = 2500 kg/m^3 (Group B particles according with Geldart's classification). The particles were white, so we put a black card at the bed back ensuring a high contrast between bubbles and particles.

Different experiments were carried out varying the superficial gas velocity (U/U_{mf} = 2, 3 and 4) with a fixed bed height of 30 cm approximately. The terminal velocity of the smallest particles was always higher than the superficial gas velocity, therefore the entrainment was neglected. We used a High Speed Video-Camera, which took 250 photographs per second with a resolution of 480 x 512 pixels.

MEASURING THE THROUGHFLOW VELOCITY CROSSING THE DOME OF ERUPTING BUBBLES

In order to measure the throughflow velocity in 2-D erupting bubbles we assumed that the porosity of the dome formed when a bubble erupts at the bed surface is constant and equal to ε_{mf} and the pressure drop across the dome is given by Ergun's equation. This procedure has already been used by Glicksman and Yule Glicksman and Yule (9). Following their work, the dome was divided in elements and for each one the drag force of the grouped particles per unit volume was calculated through a force balance in the direction of the particle displacement, that is, perpendicular to the dome contour (10) . The resulting equation for each element is

$$\left(1-\varepsilon_{mf}\right)\rho_p \frac{d\vec{v}_p}{dt} = \overrightarrow{F_d} - \left(\overrightarrow{F_g} - \overrightarrow{F_b}\right)\sin\left(\theta\right) \quad (1)$$

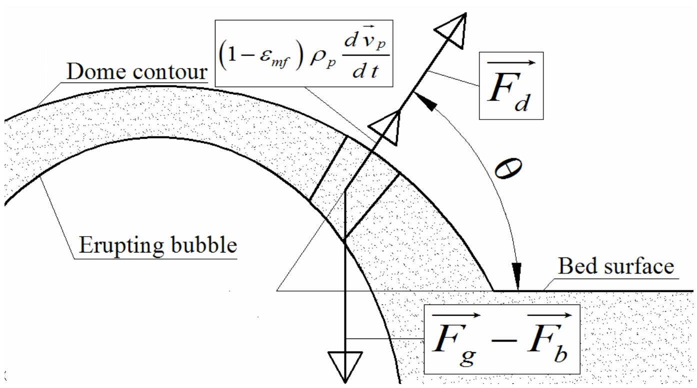


Fig. 1. *Force balance in the bubble dome*

where (1-ε_{mf}) ρ_p is the mass of particles per unit of volume, v_p is the velocity of the group of particles, θ is the angle formed by the particle velocity vector and the bed surface and F_d, F_g and F_b are the drag, gravity and buoyancy forces per unit of volume, respectively. Fig. 1 shows a sketch of the force balance.

In equation (1) the gravity and buoyancy forces are already known, because they depend only on ε_{mf}, ρ_p, ρ_g and g. The particles acceleration, a_p, was measured from the photographs using the method developed by Almendros-Ibáñez et al. (8) to measure the particle ejection velocity. Therefore, the drag force can be obtained from equation (1), assuming $\rho_g << \rho_p$, as

$$F_d = \left(1-\varepsilon_{mf}\right)\rho_p \left[a_p + \left(1-\frac{\rho_g}{\rho_p}\right) g \sin\left(\theta\right)\right] \approx \left(1-\varepsilon_{mf}\right)\rho_p \left[a_p + g\sin\left(\theta\right)\right] \qquad (2)$$

The interparticle forces are considered negligible, that is, the energy dissipated because of the pressure drop across the dome is considered equal to the sum of the energy dissipated for each particle which experiences a drag force. Then, the drag force of the grouped particles can be related with the pressure drop across the dome (11) according to the following expression

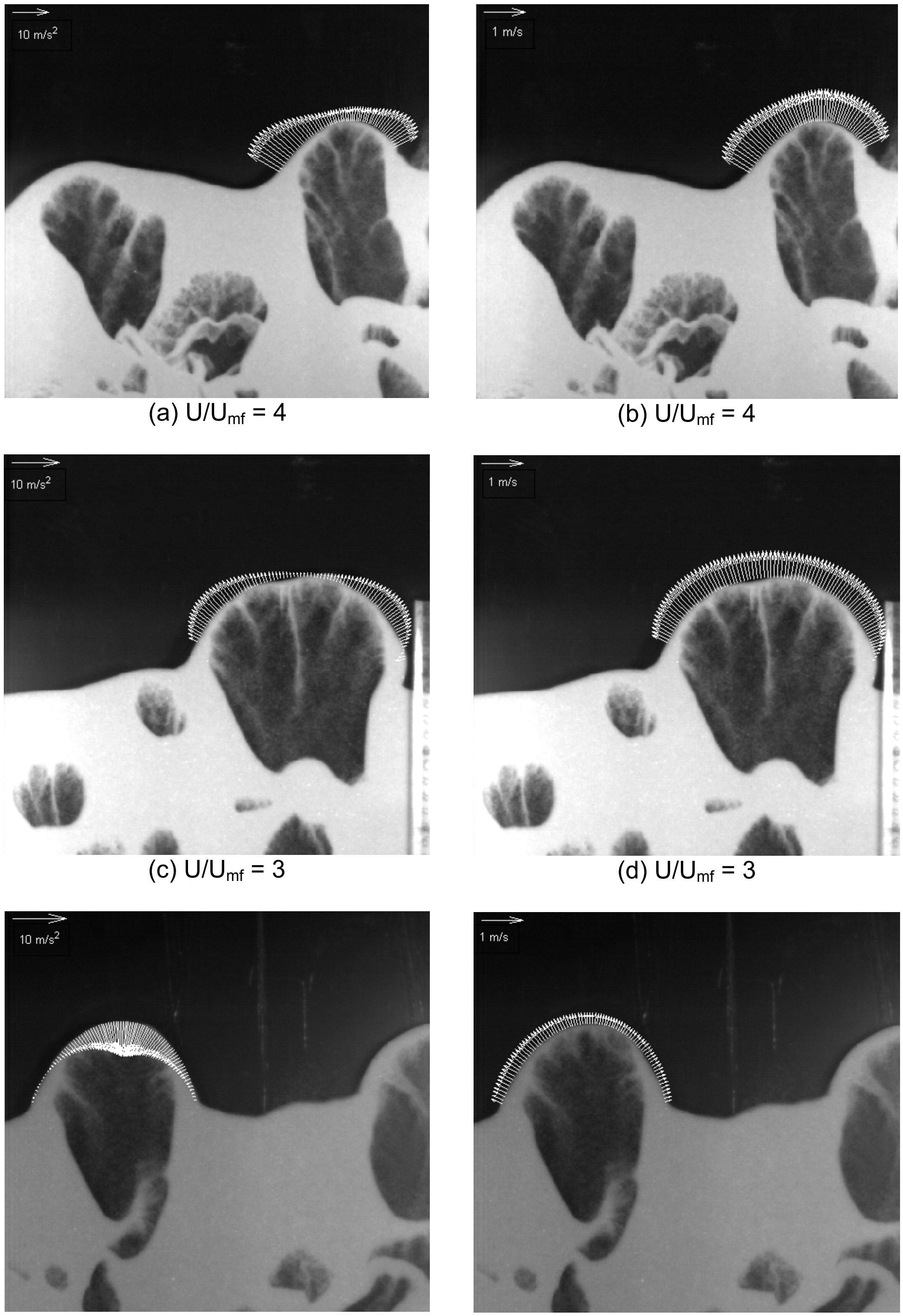
$$U_r \frac{\Delta P}{L} = \frac{U_r}{\varepsilon_{mf}} F_d \qquad (3)$$

where U_r is the superficial gas velocity relative to the dome, L is the dome thickness and ε_{mf} takes into account the change in the superficial velocity, as we considered that each particle in the dome is suspended by the interstitial velocity.

The dome thickness L was obtained from the experiments and the minimum value was ~ 5mm in the central region of the profiles. Therefore $(L/d_p)_{min}$ ~ 14 > 2 and according to Glicksman and Yule (9), ΔP/L can be obtained from Ergun's equation, which combined with equation (3) results in the following expression

$$F_d = 150\frac{\mu_g U_r}{d_p^2}\frac{\left(1-\varepsilon_{mf}\right)^2}{\varepsilon_{mf}^2} + 1.75\frac{\rho_g U_r^2}{d_p}\frac{\left(1-\varepsilon_{mf}\right)}{\varepsilon_{mf}^2} \qquad (4)$$

From equation (4) the throughflow velocity of the gas, which was defined by Gera and Gautam (4) as *"… the component of the fluid flow in a bubble, relative to the bubble, across a plane normal to the vertical axis of the bubble…"*, was evaluated.



(a) $U/U_{mf} = 4$ (b) $U/U_{mf} = 4$

(c) $U/U_{mf} = 3$ (d) $U/U_{mf} = 3$

(e) $U/U_{mf} = 2$ (f) $U/U_{mf} = 2$

Fig. 2. *Experimental measurements at different superficial gas velocities. Subfigures (a), (c) and (e) show the particle acceleration profiles (a_p) and subfigures (b) (d) and (f) the throughflow velocities profiles (U_r)*

Note that is not necessary to measure L in order to obtain U_r. Although we defined U_r as the velocity relative to the dome, our definition is analogous the one of Gera and Gautam because the dome velocity depends on the bubble velocity (8).

In order to calculate the total flux of air crossing the dome of the erupting bubble, the velocity of the gas was integrated along the dome contour. As we divided the dome in elements we do not have continuous functions of the variables. Then we evaluated the integral numerically according to equation (5)

$$\dot{V}_{bubble} = \int_{\theta_{min}}^{\theta_{max}} U_t(\theta)\, r(\theta)\, T\, d\theta \approx \sum_{i=1}^{N} U_{t_i}\, l_i\, T = \sum_{i=1}^{N} \left(U_{r_i} + v_{p_i}\right) l_i\, T \qquad (5)$$

where U_{ti}, and l_i are respectively the absolute gas velocity crossing the dome and the length of the dome's arc. N is the number of elements and T is the thickness of the bed (do not confuse with the dome thickness L).

RESULTS AND DISCUSSION

Different experiments were carried out at different superficial gas velocities. Figure 2 shows three different cases of erupting bubbles for U/U_{mf} = 2, 3 and 4. For each case the particle acceleration and the measured throughflow velocity profiles are represented.

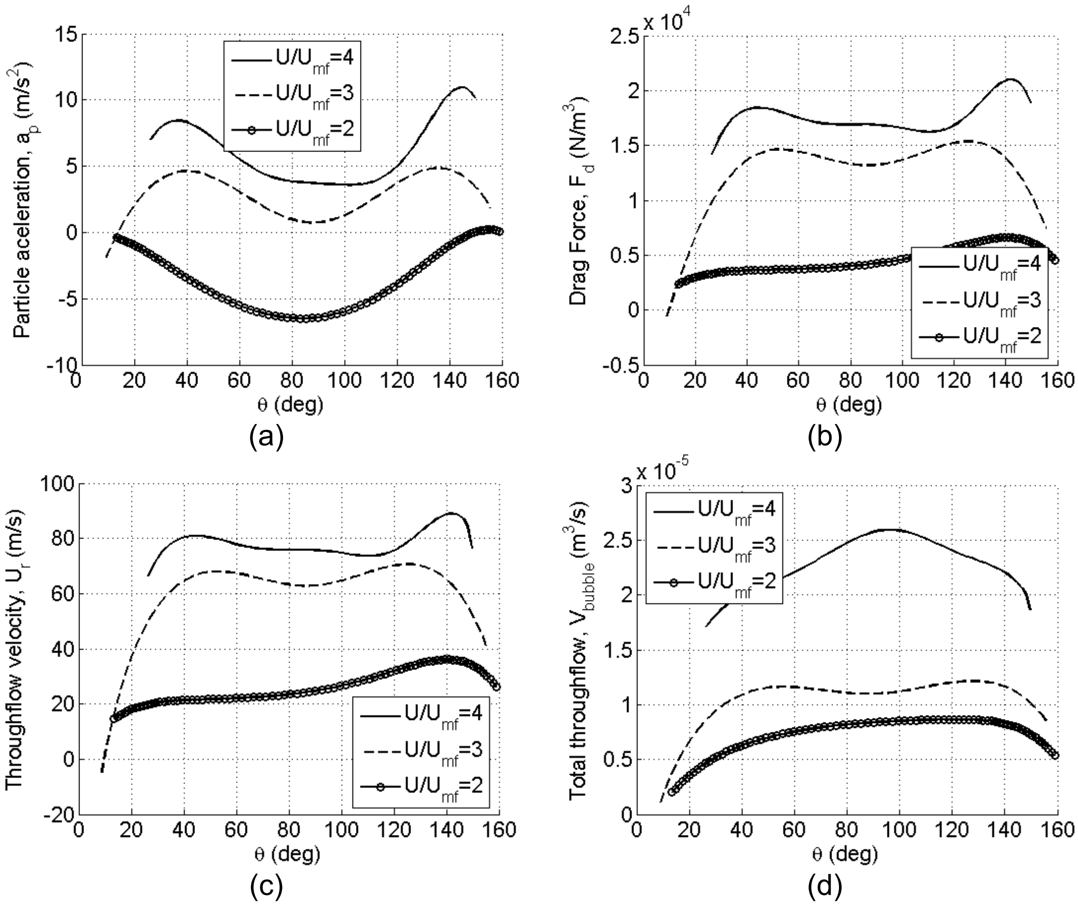


Fig. 3. *(a) Particle acceleration, (b) drag force per volume, (c) throughflow velocity and (d) total throughflow for the experiments showed in Fig. 2.*

The particle acceleration profiles in the three cases show a similar trend. The acceleration is maximum in the zone close to the stagnation points and minimum in the bubble nose. In this last region the particles displacement is nearly vertical and consequently the gravitational force is important (sin(θ) ~ 1). Therefore the drag force has to overcome the gravitational component. In contrast, when the particle displacement is horizontal (sin(θ) ~ 0), the gravitational component in equation (1) is neglected because it is almost perpendicular to the velocity of the particles. As a consequence the acceleration is higher than in the nose zone.

In some cases, like the one shown in Fig. 2.(e), the particle acceleration can be negative when the throughflow velocity is small. This is because the air, on its path to the freeboard, can be influenced by other bubbles, like a different bubble with a higher diameter or a higher aspect ratio. In this case a deep cavity is formed at the bed surface and consequently the throughflow increases in this larger erupting bubble (2). Thus, the throughflow decreases in the smaller ones.

Fig 3.(a) compares the dome acceleration profiles varying the superficial gas velocity. As it is expected, a_p increases with U. According to Fig. 3.(a) a higher drag force could be expected in the region of high dome acceleration, but in the region of low a_p the gravitational force is more significant and the drag force is balanced by both the inertial and the gravitational forces. So, the right term of equation (2) is approximately constant and consequently, the drag force profiles are flatter (see Fig. 3.(b)) than the acceleration ones in the central region (40 deg < θ < 140 deg).

The drag force profiles obtained from equation (2) were introduced in equation (4)in order to evaluate the throughflow velocity profiles. The result is shown in Fig. 3.(c) where they appear quite similar to the drag force profiles. For our experimental conditions the quadratic term of equation (4) is typically one order of magnitude lower than the linear term. This fact explains the almost linear relation between both magnitudes.

The total throughflow crossing the dome is obtained adding the particle velocity profiles to the throughflow velocity profiles (see equation (5)). As the particle velocity profiles have typically a maximum in the direction of bubble displacement (10), that is θ ~ 90 deg, the total flux crossing the dome increases in the central region (see Fig. 3 (d)). The case U/U_{mf} = 3 is a collapsed dome bubble, similar to the ones observed by Almendros-Ibáñez et al (8). For this type of erupting bubbles the particle velocity profile is atypical and has the maximum in the regions close to the stagnation points rather than in the central region. Therefore, in this case, the total throughflow does not increase noticeably in the central region.

Table 1 shows that the total flux crossing the dome of the erupting bubble increases with the superficial gas velocity. Nevertheless for our experimental conditions, in the three cases studied here, the total flux crossing the bubble dome is approximately the 10 % of the total flux crossing the cross section of the bed. Of course this result can be different if some parameters of the experimental conditions (like bubble diameter, bed width or superficial gas velocity) change.

Table 1. *Total throughflow crossing the erupting bubbles, total gas flow crossing the bed and equivalent diameter of the erupting bubble for each experiment.*

U/U_{mf}	$\dot{V}_{bubble} \times 10^4$ (m^3/s)	$\dot{V}_{bed} \times 10^4$ (m^3/s)	D_b (cm)
4	1.316	13.2	11.6
3	0.907	9.9	11.9
2	0.581	6.6	8.9

CONCLUSIONS

A new method for measuring the throughflow velocity profile of erupting bubbles in freely bubbling 2-D fluidized beds has been proposed, using a non-intrusive measurement technique. The main conclusions of the present work can be summarized as follow:

(a) The dome acceleration profiles show maximum values in the zone where the gravity component is negligible (sin(θ) ~ 0) and minimum in the nose of the dome, where sin(θ) ~ 1
(b) The dome throughflow velocity profiles are approximately uniform in the central region of dome (40 deg < θ < 140 deg). In contrast, they decrease in the region close to the stagnation points.
(c) The total throughflow can be obtained adding the particle velocity profile to the throughflow velocity profile and integrating along the dome contour, according to equation (5).
(d) For our experimental conditions, the total throughflow crossing each erupting bubble is approximately $\dot{V}_{bubble} \sim 0.1 \times \dot{V}_{bed}$, which agrees with the ratio between the bubble equivalent diameter and the bed width. Nevertheless, this result must be taken with caution because it depends on the bubble diameter, the bed width, the height of the fixed bed and the superficial gas velocity. A further analysis is necessary varying these parameters.

NOTATION

a_p	Particle acceleration [m/s^2]
D_b	Bubble equivalent diameter [m]
d_p	Particle diameter [m]
F_b	Buoyancy force [N/m^3]
F_d	Drag force [N/m^3]
F_g	Gravity force [N/m^3]
g	Gravity constant [m/s^2]
L	Dome thickness [m]
l	Length of the dome's arc [m]
r	Radius of curvature of the dome's arc [m]
T	Bed thickness [m]
U	Superficial gas velocity [m/s]
U_{mf}	Minimum fluidization velocity [m/s]

U_t Absolute throughflow velocity [m/s]

U_r Throughflow velocity [m/s]

$\dot{V}_{bed}$ Total flux crossing the bed [m^3/s]

$\dot{V}_{bubble}$ Total flux crossing the dome [m^3/s]

v_p Particle velocity [m/s]

ΔP Pressure drop across the dome [Pa]

ε_{mf} Porosity at minimum fluidization conditions [-]

μ_g Dynamic viscosity of the gas [Pa·s]

ρ_g Gas density [kg/m^3]

ρ_p Particle density [kg/m^3]

θ Angle formed by the particle displacement direction and the bed surface [deg]

REFERENCES

(1) H. A. Masson, 1978. *"Solid circulation studies in a gas-solid-fluid bed"*. Chemical Engineering Science, 5, 621-623

(2) L.R. Glicksman and T.W. Yule, 1986. *"Gas throughflow in a bubbling fluidized bed"*. Proceedings of the Engineering Foundation Conference, Fluidization V, Elsinore, Denmark

(3) E.K. Levy, H.K. Chen, R. Radcliff and H.S. Caram, 1988. *"Analysis of gas flow through erupting bubbles in a gas-fluidized bed"*. Powder technology, 54, 45-57

(4) D. Gera and M. Gautam, 1994. *"Variation of throughflow velocity in a 2-D rising bubble"*. Powder Technology, 79, 257-263

(5) D. Gera and M. Gautam, 1995. *"Effect of bubble coalescence on throughflow velocity in a 2-D fluidized bed"*. Powder Technology, 83, 49-53

(6) D. Gera and M. Gautam, 1993. "*Effect of voidage variation and bubble aspect ratio on throughflow in 2-D elliptical bubbles*". Powder Technology, 79, 159-165

(7) L. Hailu, F. Plaka, R. Clift and J.F. Davidson, 1993. *"Measurement of gas-flow through a 2-dimensional bubble in a fluidized bed"*. Chemical Engineering Research & Design, 71, 382-389

(8) J. A. Almendros-Ibáñez, C. Sobrino, M. de Vega and D. Santana, 2006. *"A new model for ejected particle velocity from erupting bubbles in 2-D fluidized beds"*. Chemical Engineering Science, 61, 5981-5990

(9) L.R. Glicksman and T. Yule, 1995. *"Prediction of the particle flow conditions in the freeboard of a freely bubbling fluidized bed"*. Chemical Engineering Science, 50, 69-79

(10) D. Santana, S. Nauri, A. Acosta, N. García and A. Macías-Machín, 2005. *"Initial particle velocity spatial distribution from 2-D erupting bubbles in fluidized beds"*. Powder Technology, 150, 1-8

(11) P.U. Foscolo, L.G. Gibilaro and S.P. Waldram, 1983. *"A unified model for particulate expansion of fluidised beds and flow in fixed porous media"*. Chemical Engineering Science, 38, 1251-1260.