DEPENDENCE OF THE TOTAL ENTRAINMENT FLUX UPON THE APPARENT AND THE TOTAL FLUIDIZATION NUMBER

by

Valentino M. STOJKOVSKI, Zvonimir A. KOSTIĆ and Aleksandar T. NOŠPAL

Original scientific paper
UDC: 532.529:533.6.01/.06–912
BIBLID: 0354–9836, *4* (2000), 1, 65–73

Since the fluidization curve of polydispersive materials has a transition area, the apparent and the total minimum fluidization velocity can be defined. Therefore, the dependence of the total entrainment flux upon the apparent and the total fluidization number were investigated. Experiments were performed in 200 mm diameter glass column, with mixtures of coarse and fine particles of silica sand as bed materials. The influence of bed material structure, fluidization number (apparent and total), bubble diameter and freeboard height are taken into consideration in the analysis of the experimentally obtained results for total entrainment flux.

Introduction

Particles are splashed into the freeboard when bubbles burst at the bed surface. The basic ejection mechanisms emphasize the role of the bubble nose (roof) particles, the particles in the bubble wake or both nose and wake particles. The picture is further complicated by the freeboard effects in which particles are transported upward as dispersed particles or as agglomerates, and downwards near the wall of the column as a flowing suspension or in the center as larger agglomerates.

Superficial gas velocity, bed compositions, particle size and freeboard height are dominant factors in the total entrainment flux of particles from bubbling fluidized bed (Geldart, D., 1985, Stojkovski *et al.*, 1996). Experimental observation have shown that the total flux is proportional to different variables in the following manner:

- superficial gas velocity to the 4th-6th power
- particle density to the -4th power
- particle size to the -2nd power
- gas density to the 1st power
- a factor of 10 in rising disengaging heights from 1,5 m to 7,5 m above which height negligible change is observed.

The change of the total entrainment flux of particles through the freeboard height, Lewis *et.al.* 1962 described by the equation in the form:

$$\frac{E}{U_f} = C \cdot \mathrm{e}^{-\frac{b_0 + A_s U_f z}{U_f^2}} \tag{1}$$

where is $b_0 = 1.26 \cdot 10^6 \rho_p d_{pm}^2$, and C is constant depended on physical characteristics of material and dimensions of column.

Tweddle *et al.*, 1970, for description of the experimental results used the approximate equation in the form

$$\frac{E}{U_f} = K_1 \mathrm{e}^{\frac{k_2}{U_f^2} + K_3 z} \tag{2}$$

where the values of coefficients K_1, K_2 and K_3 are strictly derived for his experimental conditions.

Kunii and Levenspiel, 1990, proposed a theoretically model to represent the complex phenomena occurring in the freeboard above a fluidized bed. With the developed one-dimensional model, they confirmed exponential low of the change of particle flux along a freeboard height.

For the interpretation of the experimental results, Large *et al.*, 1976, used the following equation:

$$E = E_\infty - E_0 \mathrm{e}^{-az} \tag{3}$$

where E_∞ is the elutriated rate of particles above the *TDH*. This model is based on the elementary presumptions, *i. e.* if the fluidization velocity is constant, then the elutriated rate of particles above the *TDH* is constant, and that the decrease of the entrainment flux along the freeboard height is exponential. At height of freeboard near the bed surface, $z \approx 0$, this model takes into account the elutriated flux of particles E_∞ twice.

This irregularity of Large's model is corrected by Wen and Chen 1982, by using the following equation:

$$E = E_\infty + (E_0 - \mathrm{E}_\infty) \mathrm{e}^{-az} \tag{4}$$

where the value of a varies from 3.5 to 6.4 m^{-1}. Since this value is not very sensitive on the conditions in the freeboard, it is recommended that a value of 4.0 m^{-1} can be used for systems in which no information on entrainment rate is available.

Because all above mentioned models don't contain height of the bed, Stojkovski *et al.*, 1997b proposed new one-dimensional model, based on the Wen-Chen, equation:

$$E = E_\infty + (E_0 - \mathrm{E}_\infty) \mathrm{e}^{-H(\alpha H + \beta)} \tag{5}$$

where α and β are linearly interrelated, after using a correction on coefficient β for the value of the bed height.

George and Grace, 1981, on the base of mechanistic manner of looking at the entrainment which considered the ejected particles at the bed surface and the fraction of particles which are carried over, proposed that the ejection flux is:

$$E_0 = \eta_{fb} \xi k \phi \rho_p (1 - \varepsilon_{mf}) f_w (U_f - U_{mf}) \tag{6}$$

where ϕ is the mass fraction of fine particles, f_w is the volume occupied by the wake divided by the bubble volume ($f_w \approx 0.2$), $k = G_B/(U_f - U_{mf})A_s$ accounts for deviations from the two-phase theory of fluidization ($k \approx 0.5$), and η_{fb} is the fraction of entrainable particles ejected into the freeboard which penetrate beyond the disengaging section, ξ is fraction of wake particles ejected into the freeboard ($\xi \approx 0.4$).

Several proposed models contain particle flux at bed surface as a parameter E_0. For this quantity Wen and Chen, 1982, proposed an empirical correlation

$$\frac{E_0}{A_s D_b} = 3.07 \cdot 10^{-9} \frac{\rho_f^{3.5} g^{0.5}}{\mu_f^{2.5}} (U_f - U_{mf})^{2.5} \tag{7}$$

obtained by extrapolation of the entrainment rate in the freeboard to the bed surface.

In this work, dependence of the total entrainment flux upon the apparent and the total fluidization number is analyzed. Possibility to correlate experimental data for bubble diameter in pre-eruption with total number of fluidization shown by Mickovska A. *et.al.*, 1997, was the reason why in this work total entrainment flux is analyzed in function of the total number of fluidization.

Experiments

Material

The bed material was silica sand with particle density $\rho_p = 2660$ kg/m^3 . Two narrow fractions of the bed material were used in the experiments: a fraction with equivalent diameter of particles $d_{pm}^F = 0.1487$ mm (approximately fine – F) and a fraction with $d_{pm}^P = 0.5798$ mm (approximately coarse – P), as well as their mixtures: P20/F80 (20% coarse and 80% fine material), P40/F60., P60/F40, and P80/F20. The main physical properties of the bed mixtures are given in Table 1.

Table 1. The main physical properties of bed mixtures (Stojkovski, V., 1995

Material	F	P20/F80	P40/F60	P60/F40	P80/F20	P
d_{pm} [mm]	0.1487	0.1760	0.2202	0.2769	0.2788	0.5798
ρ_o [kg/m^3]	1280	1345	1395	1406	1410	1420
ε_o [–]	0.5188	0.4944	0.4756	0.4714	0.4699	0.4662
$U_{mf\text{–}P}$ [m/s]	0.0359	0.0403	0.0542	0.1078	0.1328	0.302
$U_{mf\text{–}T}$ [m/s]	0.0910	0.1090	0.130	0.16	0.2340	0.302

Minimum fluidization velocity

The experimental procedure for determining the minimum fluidization velocity U_{mf} consist of the recording the fluidization curve, *i. e.* $\Delta p = f(U_f)$, and by using of the grapho-analytical method (Oka, 1994). Apparent minimum fluidization velocity, U_{mf-P}, is determined at the intersection of the straight line defined by the experimental data measured in filtration state of the bed and the line defined by data measured in fluidized state of bed. As a total minimum fluidization velocity, U_{mf-T}, is adopted the value of the velocity, at which there appears a deviation of the fluidization curve from the line which is drawn in the area of the fluidized bed, Fig. 1a. The relation U_f / U_{mf} is termed as a fluidization number.The fluidization curves obtained for different mixtures are presented in Fig. 1b. The fluidization curves are presented as a dependency holding between the gas velocity in the column and the specific pressure drop of the bed Δp_{ek}, defined as a ratio between the total value of the pressure drop of the bed Δp and the bed weight gm_{sl}, reduced to a unit cross section of the column A_s, *i. e.*:

$$\Delta p_{ek} = \frac{\Delta p}{\frac{1}{A_s} m_{SL} g} = f(U_f) \tag{8}$$

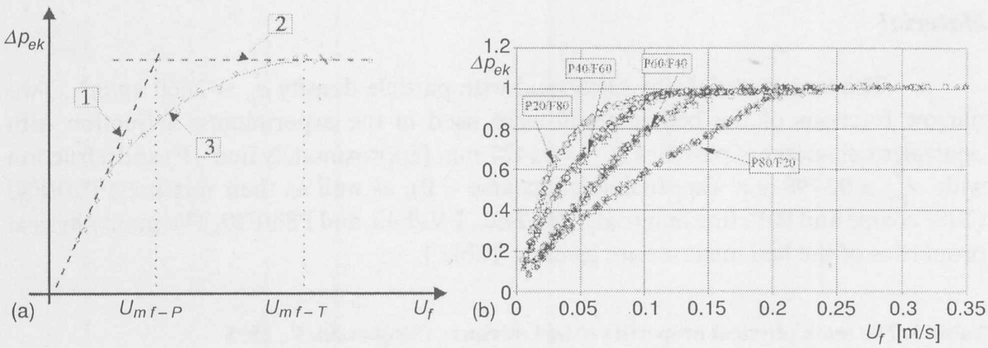


Figure 1. Defining the value of the apparent and total minimum fluidization velocity

Bubble diameter

The experimental determination of the bubble diameter was performed in two-dimensional bed, in the zone of bubble pre-eruption using video based method. Bubble diameter was read from video recordings (24 frames/second), for fluidization velocities within the following interval $U_f = 0{,}3$–$0{,}95$ m/s and for bed initial heights $h_0 = 150$

and 230 mm for 4 different bed materials. Bubbles were measured at distance from the distributor plate: $h_m = 260 \pm 30$ mm for $h_0 = 230$ mm and $h_m = 170 \pm 20$ mm for $h_0 = 150$ mm. Those are distances at which bubbles are about to burst on the surface, but are still observed stable (pre-eruption region).

Considering the presentation of experimental results in function of total number of fluidization, shown on Fig. 2b, we can make the following conclusions, Stojkovski *et. al.*, 1997a:

– the pre-eruption bubble diameter experimental data can be correlated irrespective of the particle size distribution or mixture composition of the material used;
– dependence of the pre-eruption bubble diameter on total number of fluidization can be described with a single curve.

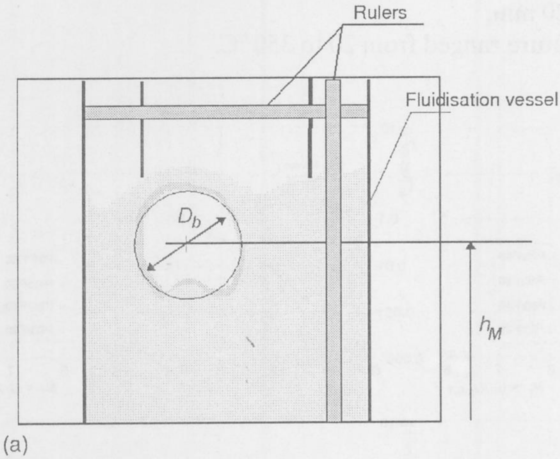
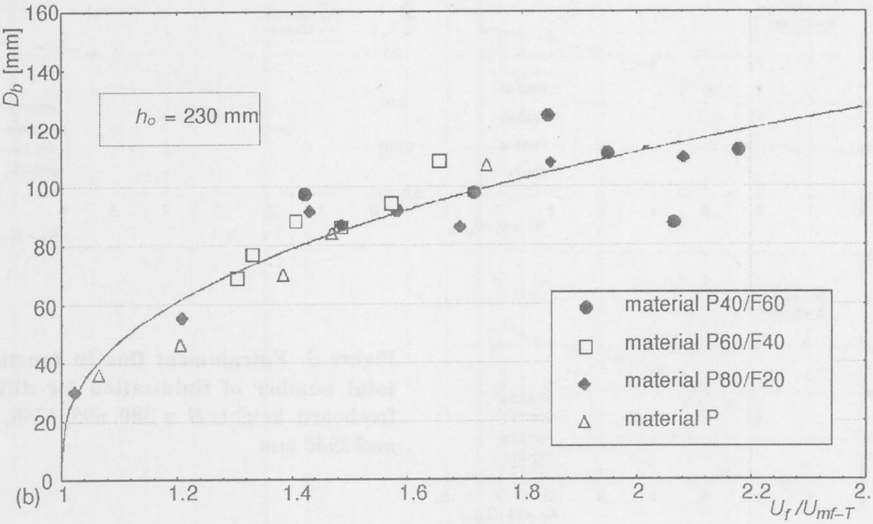


Figure 2. Pre-eruption bubble diameter correlated by total number of fluidization, for different tips of the bed material

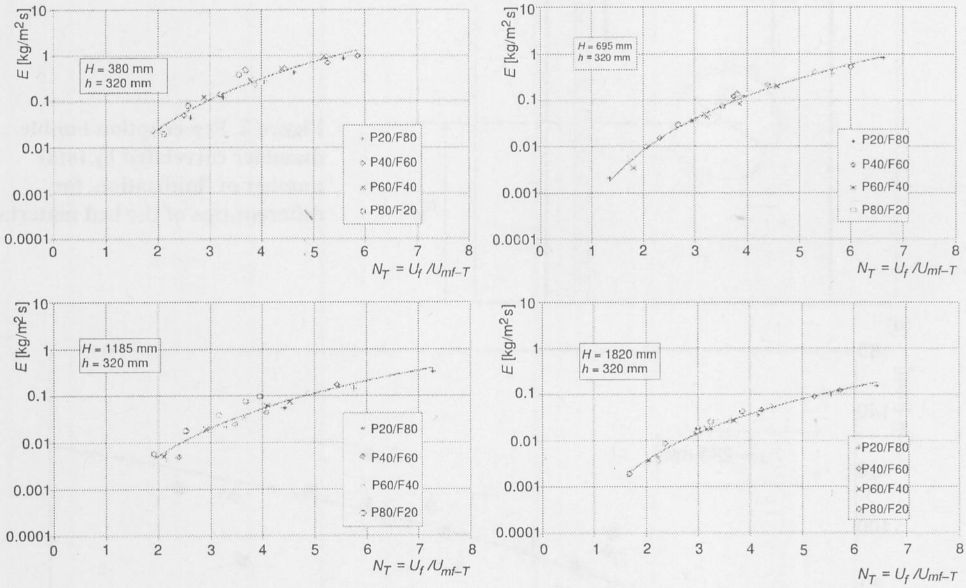


Entrainment of particles

The research of particles entrainment was carried out for different bed material compositions. During experiments a continuos feeding and discharging of the material from the bed were maintained. The cylindrical column with a diameter D_s = 200 mm was made of glass and PVC parts. The experimental apparatus is described in details in the previous work by Stojkovski *et. al.,* 1995. A conical section with dimensions 200/50/150 mm was added at the top of the column. The amount of entrained material was collected by a filter cloth. Air was used as fluidizing gas. The rate of air flow was measured by a orifice inserted in 36 mm diameter pipe-line.

The experiments presented in this paper were carried out for:

– the air flow velocity ranged from U_f = 0.3–0.9 m/s;
– the freeboard heights H = 380, 695, 1180, 1850, and 2940 mm;
– fluidized bed height h = 320 mm,
– the fluidization air temperature ranged from 20 to 350 °C.



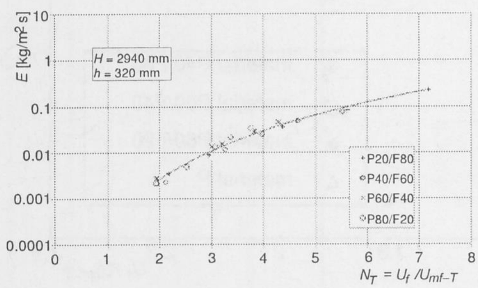


Figure 3. Entrainment flux in function of total number of fluidization for different freeboard heights H = 380, 695, 1180, 1820, and 2940 mm

Results

Figure 3 illustrates the changes on the total entrainment flux of particles at different heights of air offtake, *i. e.* at different freeboard heights, and for various total fluidization number for different mixtures.

As it can been seen, the experimentally obtained data for entrainment particle flux in function of the total number of fluidization, $N_T = U_f/U_{mf-T}$, are grouped along the single lines irrespective of the bed material used.

The change of the entrainment particle flux, E in terms of the freeboard height, for three values of fluidization number N = 3, 4 and 5 is presented in Fig. 4. The diagrams in Fig. 4 are obtained from functions $E = f(U_f)$, given in Stojkovski *et al.*, 1995, because in the present experiments, due to technical reasons, the superficial gas velocity could not be maintained constant.

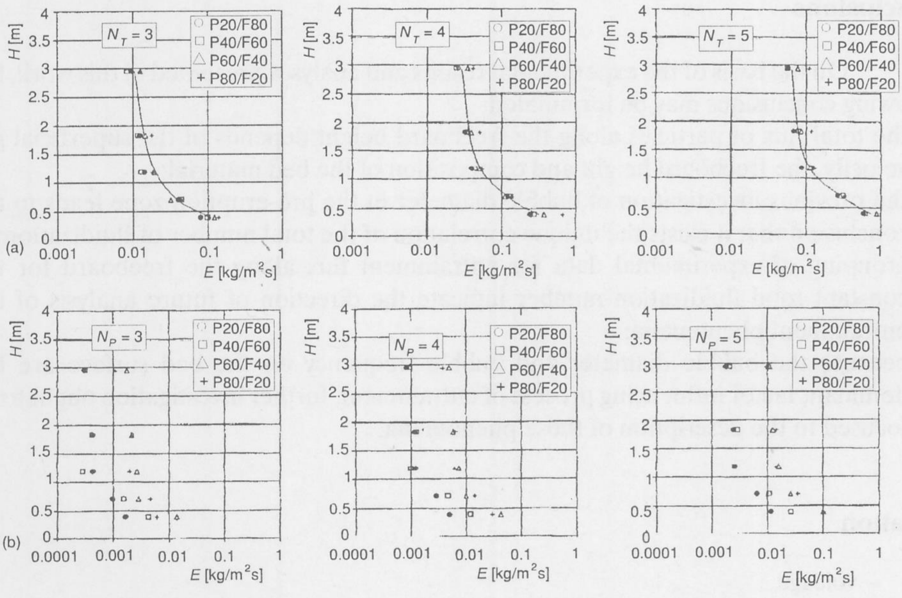


Figure 4. Change of the entrainment particle flux along the freeboard height
(a) for the three different total fluidization numbers
(b) for the three different apparent fluidization numbers

The results obtained show that the influence of freeboard height on particle separation is obvious. At a constant number of fluidization, by increasing the freeboard height, the separation of particles is finer. Therefore, the flux of entrained particles decreases and has a tendency of acquiring a constant value, which is consequence of attaining the *TDH*. The particle entrainment flux is greater at lower freeboard heights. For the present experimental condition the influence of the freeboard height is present up to *cca* 2m.

As it can been seen, the same results presented as a function of the total and the apparent fluidization number give a different picture. Grouping of the experimental data for the flux of entrained particles along the freeboard, for the same total fluidization number, Fig. 4, is not influenced by the mixture composition of the material used. This is the reason for using the total minimum fluidization velocity in further analysis of the entrainment phenomena.

The experimentally obtained correlation for pre-eruption bubble diameter in function of total fluidization number and presented correlation for entrainment flux along the freeboard height for constant total fluidization number, give us the possibility to formulate more simple empirical correlation. That will be the aim of investigations.

Conclusions

On the basis of the experimental results and analyses presented in this work, the following conclusions may be formulated:

- the total flux of particles along the freeboard height depends of the superficial gas velocity, the freeboard height and composition of the bed material;
- the previous investigation of bubble diameter in the pre-eruption zone leads to the conclusion that it exists the unique correlation of the total number of fluidization;
- grouping of experimental data for entrainment flux along the freeboard for the constant total fluidization number indicate the direction of future analysis of the entrainment phenomena;
- because the bubble diameter and bubble frequency on the bed surface are the dominant factor influencing process of entrainment, further investigation ought to be focused to the description of those phenomena.

Notation

ε – voidage
ρ_f – gas density
ρ_p – particle density
μ_f – dynamic viscosity
a – constant of freeboard
α – coefficient of newly proposed expression
β – coefficient of newly proposed expression
A_s – cross section of the column
D_{bo} – bubble diameter
d_{pm} – mean particle diameter of the bed material
E – total entrainment flux at height H
E_∞ – flux of elutriated particles (entrainment at height above *TDH*)
E_0 – total entrainment flux at the bed surface

F – fine particles
P – coarse particles
Δp – pressure drop across the bed
h – bed height
H – freeboard height
U_f – superficial gas velocity
U_{mf-P} – apparent minimum fluidization velocity
U_{mf-T} – total minimum fluidization velocity
N_T – total fluidization number
N_P – apparent fluidization number
m_{sl} – mass of the bed material
z – distance from the bed surface

References

[1] Geldart, D., Elutriation, Fluidization, 2nd edition (Eds. Davidson J.F., Clift R., Harrison D.), Academic Press, 1985, pp. 383–411
[2] George, S. E., Grace, J.R., Entrainment of Particles from a Pilot Scale Fluidized Bed, *The Canadian Journal of Chemical Engineering, 59* (1981), pp. 279–284
[3] Large, J. F., Martinie, Y., Bergougnou, M. A., Interpretative Model for Entrainment in a Large Gas Fluidized Bed, *Proceedings*, International Powder & Bulk Solids Handling & Processing Conference, 1976, pp.1–28
[4] Lewis, W. K., Gilliland, E. R., Lang, P. M., Entrainment from Fluidized Bed, *Ch. Eng. Progress Symposium Series, Vol. 58* (1962), 38, pp. 65–78
[5] Mickovska, A., Kostić, Z., Stojkovski, V., Nošpal, A., Mathematical Model of the Dependence of Eruption Bubble Diameter on Total Number of Fluidization in Two Dimensional Fluidized Bed, *Proceedings*, 1st South East European Symposium, Ohrid, R. Macedonia, 1997, pp. 53–62
[6] Oka, S., Combustion in Fluidized Bed (in Serbian), Jugoslovensko društvo termičara, Beograd, 1994
[7] Kunii, D., Levenspiel, O., Entrainment of Solids from Fluidized Beds: I Hold up of Solids in the Freeboard; II Operation of Fast Fluidized Beds, *Powder Technology*, (1990), 61, pp. 193–206
[8] Stojkovski, V., Elutriation and Entrainment of Particles from Fluidized Bed, M. Sc. Thesis, Faculty of Mechanical Engineering, Skopje,1995
[9] Stojkovski, V., Kostić, Z., Nošpal, A., Bundalevski, T., Parameters Influencing Fluidized Bed Particles Entrainment, *Thermal Science, 22* (1996), 4, pp. 269–280
[10] Stojkovski, V., Kostić, Z., Nošpal, A., Mickovska, A., Experimental Determination of Minimum Fluidization Velocity and Bubble Diameter in Two-Dimensional Fluidized Bed, *Proc. Fac. Mech. Eng. Skopje*, 1 (1997a), No. 16, pp. 91–98
[11] Stojkovski, V., Kostić, Z., Nošpal, A., Particles Flux Distribution in the Fluidized Bed Freeboard, *Proceedings*, 1st South East European Symposium, Ohrid, R. Macedonia, 1997b, Vol.1, pp. 85–96
[12] Tweddle, T. A., Capes, C. E, Osberg, G. L., Effect of Screen Packing on Entrainment from Fluidized Beds, *Ind. Eng. Chem. Process Des. Develop*, 9 (1970), 1, pp. 85–88
[13] Wen, C. Y., Chen, L. H., Fluidized Bed Freeboard Phenomena: Entrainment and Elutriation, *AIChE Journal, 28* (1982), 1, 1982, pp. 117–128

Authors' addresses:

V. M. Stojkovski, Z. A. Kostić, A. T. Nošpal
University "St.Kiril i Metodij", Faculty of Mechanical Engineering
P.O.Box 464, 91000 Skopje, R. Macedonia
tel: + 389 91 399 234; E-mail: tino@ereb.mf.ukim.edu.mk

Paper submited: March 9, 2000
Paper revised: April 15, 2000
Paper accepted: May 15, 2000