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ON THE PRESENCE OF PARTICLES AT THE WALL OF GAS FLUIDIZED BEDS

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ABSTRACT

In this study, the role of hydrodynamics of the dense bed on the particle convection is outlined. The existing models in the literature suggest a constant decrease of particle-wall contact time with an increase in the gas velocity. However, it has been experimentally shown that the contact time increases both in bubbling and turbulent regimes upon increasing the gas velocity. A comprehensive model is developed to represent such a trend and improve agreement with experimental data presented in literature. Comparison of predicted results with the experimental data from the literature confirms the validity of the present model for the dense bed region of fluidized bed of sand particles.

INTRODUCTION

The heat transfer process of particle to wall, induced by the particle motion within the bed, is concerned with the heat transfer from a surface when it is in contact with the particulate emulsion phase instead of the void/bubble phase. In the last 40 years, both mechanistic and empirical models have been used to describe particle-convective heat transfer in gas fluidized beds. Mickley and Fairbanks (1) stated that particle convective heat transfer could become significant in bubbling fluidization regime due to the large heat capacity of the bed materials. Their studies show that convective motion of packets of particles is responsible for the heat transfer from the wall to the bed in the bubbling fluidized bed. Molerus et al. (2) studied particle motion at the solid surface with luminosity image analysis method and found the particle migration from the solid surface. Wang and Rhodes (3) investigated the particle-wall contact time distribution by simulation and found an exponential decay for contact time distribution. Hamidipour et al. (4) also determined an exponential decay for the contact time distribution and found a bathtub shape for particle-wall contact time in the dense region of fluidized beds.

While many studies have been conducted on heat transfer in bubbling fluidized bed, only few studies have been conducted in turbulent fluidization due to complexity of the phenomena within this regime. In this work, a new model is developed for determining of particle residence time on heat exchanger surface base on particles behavior near the surface. These analyses and models are applicable to both bubbling and turbulent fluidized beds.

MODEL DEVELOPMENT

Particles in a fluidized bed could exist as individual particles, part of clusters or associated with bubbles. Mostoufi and Chaouki (5) indicated that solids in a fluidized bed do not move independently in dense bed but as aggregates such as bubble wakes, bubble clouds and clusters. Therefore, the mean residence time of emulsion phase expressed by Lu et al. (6) cannot represent the contact time of clusters and particles in cloud and wake. Likewise, the main deficiency of the model proposed by Martin (7) is that the existence of particles in form of clusters and behaviour of clusters in a dense fluidization regime are not considered.

It is assumed in this work that at any given time, the heat exchanging surface is covered by bubbles, clusters and individual particles. In general, mean residence time of particles on heat exchanging elements as well as the corresponding heat transfer coefficient depend on the hydrodynamics of fluidized bed. Any change in hydrodynamics would alter the mechanism of heat transfer between the heat exchanging surface and the fluidized bed. Individual particles exist only at very low and very high superficial gas velocities while fraction of individual particles at bubbling and turbulent regimes of fluidization may be negligible. Consequently, the contact time of solids at wall could be expressed as:

$$\tau = t_{pc} + t_{ce} \tag{1}$$

where t_{pc} is the contact time of particles with bubble and t_{ce} is the contact time of clusters in the emulsion phase. It has to be noted that the effect of isolated particles is neglected in this equation due to the fact that the portion of such particles in the bed is negligible (5).

Since the fraction of time that the surface is bathed by particles with bubbles is proportional to the volume fraction of emulsion in the vicinity of the surface, the contact time of single particles within cloud and wake can be expressed as:

$$t_{pc} = a \frac{\delta_e}{\frac{\delta_b V_b}{d_b}} \tag{2}$$

Since the bubbles in the bed make the clusters to be formed and also to be pushed towards the wall, it is assumed that the contact time of the clusters in the emulsion phase to be proportional to the bubble fraction:

$$t_{ce} = b \frac{\delta_b}{\frac{\delta_c V_c}{d_c}} \tag{3}$$

Hence, the new formula for the particle-wall contact time can be expressed as:

$$\tau = a \frac{\delta_e}{\frac{\delta_b V_b}{d_b}} + b \frac{\delta_b}{\frac{\delta_c V_c}{d_c}} \tag{4}$$

Formulas required to calculate τ based on Eq. (4) are given in Table 1. It worth noting that the cluster fraction formula shown in this table is an estimation based on the assumption that the particles in the emulsion exist only as clusters and existence of single particles in the emulsion phase is negligible. It is clear that Eq. (4) without *a* and *b* is developed within the bed, while the probability of existence of bubbles and clusters in vicinity of the wall is different from that in the bed. Correction factors *a* and *b* are introduced in order to include the wall effect. These constants should be chosen based on experimental values of the radial distribution of clusters and bubbles in the bed which is described in the followings.

Table 1 Summary of equations required for calculating particle-wall contact time in a dense fluidized bed of sand particles

Emulsion fraction	$\delta_e = 1 - \delta_b$
Cluster fraction	$\delta_c = \delta_e \left(1 - \varepsilon_e\right)$
Bubble velocity (8)	$V_b = U_0 - U_{mf} + 0.71\sqrt{g d_b}$
Bubble diameter (9)	$d_b = 0.21 H^{0.8} \left(U_0 - U_{mf}\right)^{0.42} \exp\left[-0.25\left(U_0 - U_{mf}\right)^2 - 0.1\left(U_0 - U_{mf}\right)\right]$
Descending cluster diameter (10)	$d_c = \exp\left[-0.79 + 1.555\left(U_0 - U_{mf}\right)\right]$
Ascending cluster diameter (10)	$d_c = \exp\left[-0.45 + 1.276\left(U_0 - U_{mf}\right)\right]$
Emulsion voidage (11)	$\varepsilon_e = \varepsilon_{mf} + 0.2 - 0.059 \exp\left(-\frac{U_0 - U_{mf}}{0.429}\right)$
Bubble voidage (11)	$\varepsilon_b = 1 - 0.146 \exp\left(-\frac{U_0 - U_{mf}}{4.439}\right)$
Bubble fraction (11)	$\delta_b = 0.534 - 0.534 \exp\left(-\frac{U_0 - U_{mf}}{0.413}\right)$

EXPERIMENTAL

The radioactive particle tracking (RPT) experiments were done in a 152 mm inside diameter gas-solid fluidized bed. Air at room temperature was introduced into the bed through a conical section, passing through a stainless steel porous plate and a nozzle-type air distributor. The air flow rate was measured by an orifice plate connected to a water manometer. The solids used in the experiments were sand particles. The experiments were conducted at gas superficial velocities ranging from 0.5 to 2.8 m/s, covering both bubbling and turbulent regimes of fluidization. Based on the analysis of tracer positions, the motion of individual particles near the walls of the fluidized bed was studied.

RESULTS AND DISCUSSION

Radial Distribution of Clusters and Bubbles

Mostoufi and Chaouki (10) developed an algorithm for recognizing bubbles and clusters (either ascending or descending) based on the trajectory of the tracer moving inside the bed. The particles in the emulsion could form clusters, moving either upward or downward. In this case, the axial coordinates of the trajectory of the particle is expected to exhibit a straight line when plotted against time, heading either up or down, respectively. If the particle is associated with a bubble, its trajectory would also be a straight line with a positive slope. One would expect to observe these behaviours in the data obtained in a particle tracking experiment due to the fact that the tracer in such experiment acts as a representative of the regular particles in the bed. Above idea forms the basis of the algorithm for recognizing the portions associated with bubbles and clusters among the trajectories in the RPT experiments. The same algorithm has been adopted in the present work for identifying such species and their associated portion in the bed.

A computer program was developed which keeps track of radial distributions of the trajectory of the bubbles and clusters. More details on the algorithm of this program have been provided by Mostoufi and Chaouki (10). Examples of radial distributions of bubbles and clusters throughout the bed are shown in Figure 1. This figure shows that it is very unlikely to find bubbles close to the wall. However, the probability of existence of bubbles increases by moving from wall toward the centre of the bed. Although it is expected to observe the maximum probability of existence of bubbles at the centre of the bed, probability density distribution of occurrence of bubbles in Figure 1 exhibits a maximum in a radial position between the wall and the centre. Moreover, although it is anticipated to observe the maximum probability of clusters at the wall, probability density distribution of occurrence of clusters in Figure 1 displays a maximum in a radial position between the wall and the centre. This controversy could be explained by the fact that since most of the gas passes through the centre part of the bed, the solid tracer in the RPT experiments spends a lesser amount of time close to the centre. Also, since the particle which are close to the wall are “less active” than those far from the wall, the tracer has spent a lesser amount of time close to the wall. As a result, when dealing with the radial distribution of properties calculated from RPT data, it should be noticed that the tracer has spent most of its time in radial positions not close to the centre and the wall. In other words, the probability distributions shown in Figure 1 are in fact are multiplications of probability of the existence of those species and probability of the existence of particles at each radial position. This is the reason for decreasing the probability of the existence of bubbles at the centre and decreasing the probability of the existence of clusters at the wall in Figure 1 which does not mean that there are less bubbles in the centre or less clusters at the wall, but it is due to the fact that the tracer has been less frequently passing those regions.

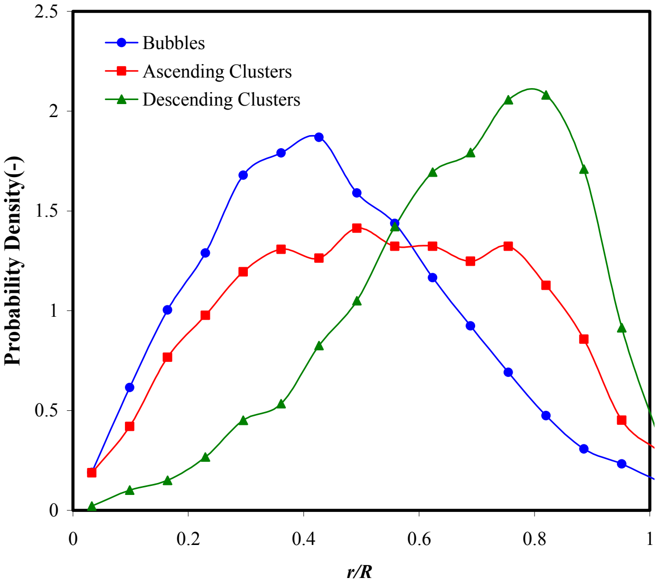

Figure 1 Radial probability density distributions of existence of bubbles and clusters in fluidized bed (U_0 = 1.5 m/s)

Based on the radial distributions of the bubbles and clusters the wall effect could be quantified for the presence of bubbles and clusters in the bed. The constants *a* and *b* in Eq. (4) are in fact correction factors for taking wall effect into account and could be evaluated from such radial distributions. In fact, the formula for particle-wall contact time was developed based on the parameters within the middle of the bed. Therefore, proper value for *a* (or *b*) would be the ratio of existence probability of bubbles (or clusters) close to wall to such a probability in the middle of the bed. Radial distributions of bubbles and clusters were calculated for the whole range of superficial gas velocity used in the experiments. These values are plotted in Figures 2 and 3. It can be concluded from these figures that, as a first-step estimation, values of *a* and *b* could be considered constant over the rage of gas velocity used in this work. The dashed lines in these figures specify the average value of these parameters and the error bars shown in the figures indicate the standard deviation of these averages. Based on these figures, average values of *a* and *b* were found to be 6.52 and 0.70 with standard deviation of 0.65 and 2.23, respectively. It is worth mentioning that the model is not sensitive to parameter *a* within the range of 0.3-1.0, and to parameter *b* within the range of 5-10. However, the proposed model with *a*=0.70 and *b*=6.52 better fits the experimental data of Hamidipour et al. (4). Therefore, values of a and b could be considered constant (as a first approximation) over the range of gas velocity used in this work. It is worth mentioning that the value of *a* obtained in this work is almost the same as the constant of the model of Lu et al. (6).

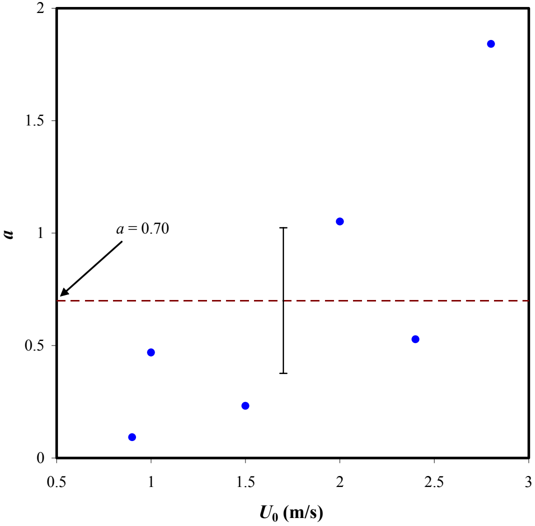

Figure 2 Existence probability ratio of bubble near wall and in the bed (a_{ave}=0.70).

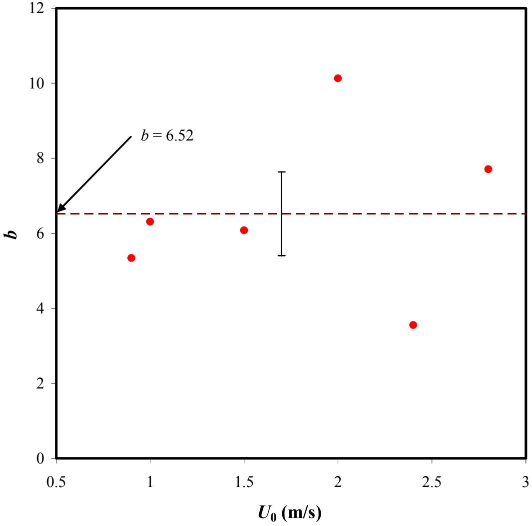

Figure 3 Existence probability ratio of bubble near wall and in the bed (b_{ave}=6.52)

Contact Time

After evaluating the constants *a* and *b*, it is possible to calculate the mean particle-wall contact time from Eq. (4). Such a calculation is performed for sand particles used in the experimental section of this work in both bubbling and turbulent regimes of fluidization. Mean values of particle-wall contact time of sand estimated by the model developed in this study is shown in Figure 3. The solid curve in this figure is drawn based on Eq. (4) with *a* = 0.70 and *b* = 6.52 and with the experimental cluster velocities [10]. The experimental data of Hamidipour et al. (4) for the contact time which were determined for the same conditions are also shown in the same figure by squares. It can be seen in Figure 3 that there is a good agreement between the proposed model work and the experimental data.

In order to demonstrate the advantage of the new model over previous models, the contact time calculated based on the expression of Lu et al. (6) is also shown in Figure 4. As could be seen in this figure, in the bubbling regime of fluidization, both models predict almost the same values and decreasing trend of particle-wall contact time. In the turbulent regime of fluidization, however, the experimental data indicate that the contact time increases with an increase in the gas velocity. In spite of this experimental fact, the model of Lu et al. (6) continues to decrease with increasing the superficial gas velocity even in the turbulent regime of fluidization while the new model shows an increase in contact time with an increase in superficial gas velocity in this regime. The most important advantage of the new model, thus, is its ability to predict the increasing trend of particle-wall contact time in turbulent regime of fluidization.

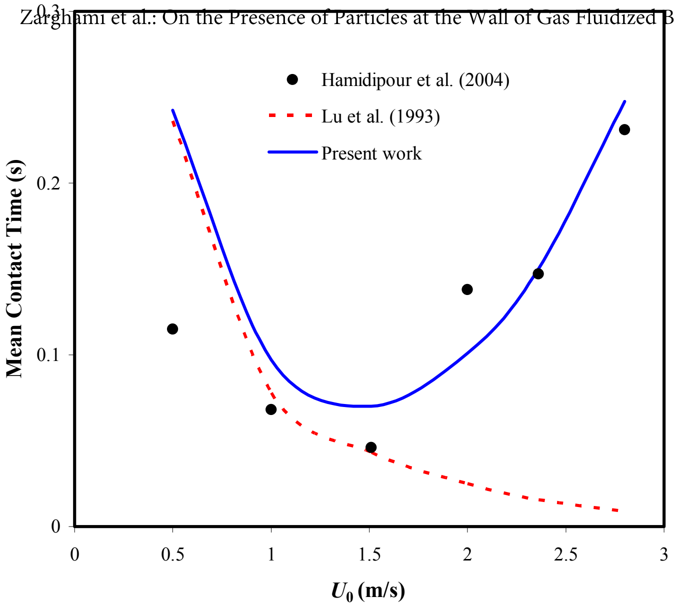

Figure 4 Variation of particle residence time as a function of superficial gas velocity, Sand particles

CONCLUSIONS

A new generalized model for mean residence time of particles at the wall of a dense gas fluidized bed is developed. In this model, it has been assumed that the particles exist mainly in the wakes of the bubble, bubble clouds and clusters in dense bed. The proposed model includes two constants for taking into account the wall effect on bubbles and clusters. These constants had to be determined experimentally. Radioactive particle tracking, an advanced method in direct imaging of particle motion, has been used for calculating radial distribution of bubbles and clusters in fluidized beds. The constants of the model were then evaluated from the radial profiles of the distribution of bubbles and clusters. The ratio of distribution values of bubble and cluster near the wall, divided to their values in a radial position in the middle of the bed were considered as model constants which acts as a correction factor for wall effect on radial existence of bubbles and clusters.

Mean particle-wall contact time, calculated based on the new model, was shown to be in agreement with the values reported in the literature. Although all previous models and correlations in the literature predict that the contact time decreases when increasing the superficial gas velocity in both bubbling and turbulent regimes of fluidization, the model developed in the present study shows that the contact time decreases in the bubbling regime of fluidization while it increases in the turbulent regime of fluidization. The mean particle-wall contact time reaches its minimum value at the onset of turbulent fluidization (U_c) in the bed of sand particles. This trend was also reported by experimental data of Hamidipour et al. (4).

NOTATION

a ratio of probability of existence of bubbles at wall and in bed

b	ratio of probability of existence of clusters at wall and in bed
d_c	cluster diameter, m
d_b	bubble diameter, m
d_s	particle diameter, m
t_{ce}	contact time of clusters in the emulsion phase, s
t_{pc}	contact time of single particles in bubble cloud, s
U_0	superficial gas velocity, m/s
U_c	superficial gas velocity at onset of turbulent fluidization, m/s
U_{mf}	minimum fluidization velocity, m/s
V_b	bubble velocity, m/s
V_c	cluster velocity, m/s

Greek letters

δ_e	emulsion fraction
δ_b	bubble fraction
δ_c	cluster fraction
ρ_s	density, kg/m^3
ρ	packet density, kg/m^3
ε_e	emulsion voidage
ε_b	bubble voidage
ε_{mf}	void fraction at minimum fluidization
τ	particle contact time at surface, s

Subscripts

p	particle
g	gas

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