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Particle-Wall Contact Time in Fluidized Beds

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Abstract: - Knowledge of the basic mechanisms of heat transfer in gas fluidized beds with immersed heat exchanger surface or bed walls is essential for any optimum design. Convective heat transfer from/to a heat exchanger surface in a gas fluidized bed can be described by the gas and/or particle convection. While many studies have been conducted on this topic, the contribution through particle convection inadequately described, especially in turbulent fluidized beds. The role of hydrodynamics of the dense bed, status of particles in form of cluster and density of clusters near the heat exchanging surface in particle convection is briefly outlined. The existing contact time models in the literature suggest a constant decrease of particle-wall contact time when increasing the gas velocity. However, it has been shown experimentally that the contact time increases in the bubbling regime of fluidization and increases in the turbulent fluidization when increasing the gas velocity. A theoretical stochastic model is developed to represent such a trend and improve agreement with experimental data presented in literature. The comparison of predicted results with latest experimental data from literature confirms the validity of the present model for fluidized bed of sand particles in the dense section of the bed.

Key-Words: - Contact Time, Fluidization, Heat Transfer, Particle Convection

1 Introduction

Convective heat transfer between gas fluidized bed and a heat exchanging surface is contributed by two major components: particle convection and gas convection. This convective heat transfer could be written as:

$$Q = h_c\left(T_b - T_s\right) \tag{1}$$

where h_c is the overall convective heat transfer coefficient which can be presented as:

$$h_c = \delta_e h_{pc} + \delta_b h_{gc} \tag{2}$$

where δ_e and δ_b are fractions of emulsion and bubble phases, h_{pc} is the particle convective heat transfer coefficient and describes heat transfer due to the motion of solids carrying heat to and from the surface and h_{gc} is the gas convective heat transfer coefficient describing the transfer of heat by motion of gas between the particles.

While the gas convection component is straightforward to predict, the contribution of particle convection remains inadequately described and strongly depends on the hydrodynamics of the bed.

Regime classification for dense phase fluidization in general can be based on bubble behavior. Dense fluidization regimes include particulate fluidization, bubbling fluidization and turbulent fluidization. While many studies have been conducted on heat transfer in bubbling fluidized bed, there are only a few studies for turbulent fluidized bed due to complexity of behavior of phenomena within turbulent fluidized bed.

The process of particle to wall heat transfer, caused 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. The heat exchanging surface can either be the enclosing walls of the bed or the surface of a body immersed in the bed. In the last 40 years, both mechanistic and empirical models are used to describe particle-convective heat transfer in gas fluidized beds. Mickley and Fairbanks [1] mentioned, in bubbling fluidization regimes, particle convective heat transfer could become significant due to the large heat capacity of the solids. They established that convective motion of packets of particles was responsible for heat transfer from the wall to the bed in the bubbling fluidized bed. They introduced the packet renewal theory which needs determination of residence time of the packet at the heat exchanging surface. Based on this theory, they developed an expression for the particle convective local transient heat transfer coefficient at the wall, h_{pc}, as follows:

$$h_{pc} = \frac{1}{\sqrt{\frac{\pi t_c}{(k\rho c)_{Packet}}}} \tag{3}$$

where t_c is the residence time of the packet at the heat transfer surface and *k, ρ, c* are the thermal conductivity, density and heat capacity of the packet, respectively.

The model of Mickley and Fairbanks [1] was improved later by paying attention to both the particle packet model near the surface and residence time of packet (particles) on the heat exchanging surface. The packet theory of Mickley and Fairbanks [1] was modified by Baskakov [2] who proposed additional resistance near the wall. Subbarao and Basu [3] assumed that at any given time, the heat transfer surface was covered by clusters and bubbles and developed the packet renewal theory in circulating fluidized beds.

Effect of heat exchanger surface location and bed distributor design on density of clusters on surface also has not been explained in literatures in detail. This point is also considered in the model developed in this work.

2 Previous Models

Martin [4] studied the contact time of particles on the surface based on the concept of molecular kinetic theory applied to solid particles in a fluidized bed. Lu et al. [5] proposed that the surface-emulsion phase contact time can be estimated by assuming that the time fraction for the surface to be covered by bubbles equals the bubble volume fraction in the bed. Later, Molerus et al. [6] developed a new contact time model based on his probabilistic viewpoint of particle migration in bubbling fluidized bed.

Wang and Rhodes [7] studied particle-wall contact time by discrete element method (DEM) simulation and suggested that the particle-wall contact time distribution may be expressed by a Ziegler gamma distribution (Ziegler et al. [8]) with a shape parameter equal to one and for some cases may also be approximated by a gamma distribution of a shape parameter equal to zero.

All the above mentioned studies estimate a monotonously decreasing trend of particle-wall contact time in all fluidization regimes. Hamidipour et al. [9], however, investigated particle-wall contact experimentally and found that the particle-wall contact time in the bed of sand decreases when increasing gas velocity in bubbling regime of fluidization, reaches its minimum at the onset of turbulent fluidization and increases beyond that. In the previous models, the contact time decreases when increasing the superficial gas velocity without limitation. However, it should be noted that all these models and simulations are developed or carried out in the bubbling regime of fluidization in which the flow structure of solids is governed by the motion of bubbles in the bed. Also they only considered the contact time of individual particles in emulsion phase which cannot clearly present the contact time of clusters and particles moving alongside bubbles.

The model of Lu et al. [5] for prediction of mean contact time of an emulsion packet with the wall is related to the point bubble frequency at the surface and emulsion fraction by the expression:

$$t_c = \frac{2}{3} \frac{(1-\delta_b)}{\frac{\delta_b V_b}{d_b}} \tag{4}$$

where δ_e and δ_b are fraction of emulsion and bubble phase, d_b is bubble diameter and V_b is bubble velocity. This contact time is the mean residence time of emulsion phase and is not the actual contact time of particles (as individual particles, particles inside the clusters, or particles with bubbles) in the bed.

3 Model Development

Since particles in fluidized bed can exist as individual particles, part of clusters, or associated with bubbles, availability of particles on the surface element is related to the status of individual particles, particles inside the clusters, or particles associated with bubbles at various hydrodynamic status of the bed. Mostoufi and Chaouki [10] showed that solids in a fluidized bed do not move independently in dense bed but as aggregates such as bubble wakes, bubble clouds and clusters. Individual particles exist only at very low and very high superficial gas velocity and fraction of individual particles at bubbling and turbulent regimes of fluidization may be negligible.

Since solid particles at dense fluidization regimes do not exist independently but can move with bubbles and clusters, the mean residence time of emulsion phase which is expressed by Lu et al. [5] [Eq. (4)] is based on unrealistic idea about particles mobility and clusters status in dense fluidized bed and cannot present the contact time of clusters and particles moving with bubbles. Likewise, the main deficiency of the model proposed by Martin [4] is that the existence of particles in form of clusters and behavior of clusters in a dense fluidization regime are not considered.

It is assumed in this work that at any given time, the heat transfer surface is covered by bubbles, clusters, and individual particle. In the present work a correlation is introduced, which allows prediction of the mean residence time of particle as a part of clusters and associated with bubbles in dens fluidization regime dependence of the physical properties of the gas-solid system and the gas superficial velocity. On the other hand, major parts of particles which are moving with bubbles are located in bubble wakes and have very small contact area with heat transfer surface that usually is installed vertically. Therefore, the heat transferred by particles which are moving with bubbles only limited to the particles which are inside the bubbles cloud. This means that the areas of bubbles which are in contact with heat transfer surface include amount of single particles and related heat transfer process can proceed by the particle convection.

Another important point which is not described in detail in previous works is the location of heat exchanger surface and effect of bed distributor design on surface density of clusters. In general, the density of clusters on the wall of a gas fluidized bed with a distributor which is designed such that the major part of perforation is considered on the center of its plate and has an imperforated band on the corner, is different from immersed heat transfer surface in the center of the bed. This implies that the mean residence time of particles (clusters) depends on location of heat exchanging surface and density of clusters on heat transfer surface. This point also has to be considered in the related correlation.

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 change the mechanism of heat transfer between heat exchanging surface and the fluidized bed. With respect to status of the particles behavior in dense fluidized bed which is described in this section and start with theoretical model of Lu et al. [5], a correlation is proposed, which allows taking into account mean contact time of clusters as a function of superficial gas velocity in addition to the contact time of single particles. It is proposed that the contact time of solids at wall could be expressed as:

$$t_c = t_{pc} + t_{ce} \tag{5}$$

where t_{pc} is the contact time of single particles within bubble cloud and t_{ce} is the contact time of clusters in the emulsion phase.

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

$$t_{pc} = \frac{\delta_e}{n_b} \tag{6}$$

where n_b is the point bubble frequency:

$$n_b = \frac{\delta_b V_b}{d_b} \tag{7}$$

In the absence of enough information about the behavior of bubbles in the vicinity of the wall, the fraction of bubbles in the bed could be used instead. However, an empirical correction factor should be used to take into account the wall effect on behaviour of bubbles. Therefore t_{pc} can be obtained from combining Eqs. (6) and (7) and adding a correction factor, a, considering the wall effect:

$$t_{pc} = a \frac{\delta_e}{\frac{\delta_b V_b}{d_b}} \tag{8}$$

Since the bubbles in the bed make the clusters to form and also pushed towards the wall, the contact time of clustered in the emulsion phase is assumed to be proportional to the bubble fraction and, like the previous case, inversely proportional to point cluster frequency in the bed:

$$t_{ce} = \frac{\delta_b}{n_c} \tag{9}$$

where n_c is the point cluster frequency:

$$n_c = \frac{\delta_c V_c}{d_c} \tag{10}$$

Combining Eqs. (9) and (10) and adding another correction factor, b, for taking the wall effect into consideration, t_{ce} is obtained from:

$$t_{ce} = b\frac{\delta_b}{\frac{\delta_c V_c}{d_c}} \tag{11}$$

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

$$t_c = a\frac{\delta_e}{\frac{\delta_b V_b}{d_b}} + b\frac{\delta_b}{\frac{\delta_c V_c}{d_c}} \tag{12}$$

As it can be seen in Eq. (12), δ_b appears in both terms of the equation but in opposite direction. From one side (in the first term of equation) increase of bubble fraction in the bed increases the point bubble frequency at the surface while at the same time reduces the mean residence time of the emulsion phase. On the other side (second term of the equation) increasing bubble fraction results in pushing the emulsion toward the wall, thus, increasing the wall-particle contact time (in form of clusters). It has to be noted that due to the existence of the particles in form of cluster in the emulsion phase of dense fluidization, Eq. (12) is valid only in such a condition. Other formulas required to calculate t_c based on Eq. (12) are given in Table 1. It is 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 neglected.

4 Results and Discussion

In order to demonstrate the performance of the model developed in this work, particle-wall contact time in a fluidized bed of sand particles was evaluated in bubbling and turbulent regimes of fluidization. Properties of the sand particles, which are the same as those employed by Hamidipour et al. [9], are given in Table 2. Mean values of the particle-wall contact time of sand particles estimated by the model developed in this study is shown in Fig. 1. The solid curve in this figure is drawn based on Eq. (12) with constants of a = 1 and b = 7. Of course, it has to be noticed that these constants should be chosen based on empirical values of particle-wall contact time which would need more attention in the future studies.

The experimental data of Hamidipour et al. [9] are also shown in the same figure by squares. It can be seen in Fig. 1 that there is a good agreement between the model developed in this work and the experimental data. The most important advantage of the new model is that it is able to predict the increasing trend of particle-wall contact time in turbulent regime of fluidization.

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

Bubble fraction [11]:

$$\delta_b = 0.534 - 0.534\,exp\left(-\frac{U_0 - U_{mf}}{0.413}\right)$$

Emulsion fraction:

$$\delta_e = 1 - \delta_b$$

Cluster fraction:

$$\delta_c = \delta_e(1 - \varepsilon_e)$$

Bubble velocity [12]:

$$V_b = U_0 - U_{mf} + 0.71\sqrt{g d_b}$$

Bubble diameter [13]:

$$d_b = 0.21 H^{0.8}(U_0 - U_{mf})^{0.42} \times \exp\{-0.25(U_0 - U_{mf})^2 - 0.1(U_0 - U_{mf})\}$$

Descending cluster diameter [14]:

$$d_c = exp\{-0.79 + 1.555(U_0 - U_{mf})\}$$

Ascending cluster diameter [14]:

$$d_c = exp\{-0.45 + 1.276(U_0 - U_{mf})\}$$

Emulsion voidage [11]:

$$\varepsilon_e = \varepsilon_{mf} + 0.2 - 0.059\,exp\left(-\frac{U_0 - U_{mf}}{0.429}\right)$$

Bubble voidage [11]:

$$\varepsilon_b = 1 - 0.146\,exp\left(-\frac{U_0 - U_{mf}}{4.439}\right)$$

Table 2. Properties of sand

ρ_s (kg/m^3)	d_s (μm)	U_{mf} (m/s)	U_c (m/s)
2650	385	0.44	1.5

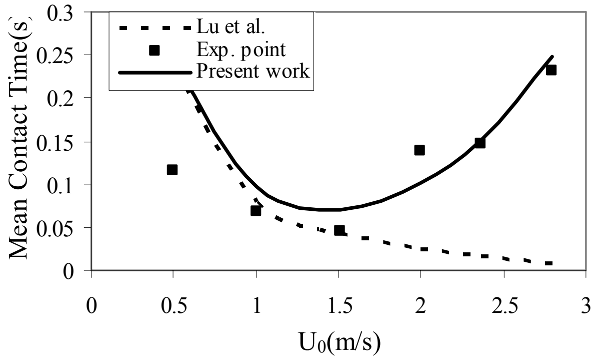

Fig. 1. Variation of particle residence time as a function of superficial gas velocity in a dense fluidized bed of sand particles

In order to demonstrate the advantage of the new model on the previous models, the contact time of Lu et al. [5], i.e., Eq. (4) is also shown in Fig. 1. As could be seen in this figure, both models predict the same values and decreasing trend of particle-wall contact time in the bubbling regime of fluidization. However, in the turbulent regime of fluidization, the model of Lu et al. [5] continues to decrease while the new model shows an increase in contact time with an increase in superficial gas velocity in this regime.

5 Conclusions

A new generalized model for mean residence time of particles at wall of a dense gas fluidized bed is presented. In this new model, it is assumed that the particles exist mainly as bubble wakes, bubble clouds and clusters in dense bed. The mean particle-wall contact time was found 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 the bed, a different trend was shown by the new model. It has been shown in this work that in a bed of sand particles the contact time decreases by increasing the gas velocity only in the bubbling regime of fluidization and increases in the turbulent regime of fluidization when the gas velocity in the bed is increased. In other words, 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 previously observed experimentally by Hamidipour et al. [9].

Nomenclature

a	wall effect correction constant in Eq. (8)
b	wall effect correction constant in Eq. (11)
c	specific heat capacity, J/kg.K
d_c	cluster diameter, m
d_b	bubble diameter, m
d_s	particle diameter, m
h_c	convective heat transfer coefficient, W/m^2.K
h_{gc}	gas convective heat transfer coefficient, W/m^2.K
h_{pc}	particle convective heat transfer coefficient, W/m^2.K
k	thermal conductivity, W/m.K
n_b	point bubble frequency, s^{-1}
n_c	point cluster frequency, s^{-1}
Q	heat transfer rate, W
T_b	bed temperature, ^{o}C
t_c	contact time, s
t_{ce}	contact time of clusters in the emulsion phase, s
t_{pc}	contact time of single particles in bubble cloud, s
T_w	wall temperature, ^{o}C
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 Symbols

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

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