Convective heat transfer scaling at the wall of circulating fluidized bed risers

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ABSTRACT

We performed experiments to establish the scaling of convective heat transfer at the wall of circulating fluidized beds. In these units, the suspension condenses into clusters separated from the wall by a gas film of order the mean particle diameter. Because of the relatively high solid volume fraction and heat capacity of these clusters, Lints and Glicksman [AIChE Symp. Ser. 89 (1993), pp. 297-304] suggested that the convective heat exchange at the wall scales with the ratio of two characteristic times.

The first is the time necessary for cluster particles to cool by conduction through the gas layer. It is proportional to the particle density, specific heat and diameter squared, and it is inversely proportional to the gas conductivity. The second is the residence time spent by clusters at the wall. It combines their residence length and mean descending velocity.

To verify the insight of Lints and Glicksman (1993a), we measured the convective heat transfer rate with a non-invasive, constant temperature probe capable of recording simultaneously the volume fraction and heat flux at the wall. We also recorded the cluster residence length using a new thermal marking technique. Finally, by inspecting data from several investigators, we established that the cluster descending velocity scales with the square root of the particle diameter and the gravitational acceleration.

The principle of our experiments was to maintain hydrodynamic similarity in the fully-developed upper region of a circulating fluidized bed riser, while conducting heat transfer measurements with gas and solid materials of different thermal properties. We investigated conditions analogous to a coal combustor pressurized to 0.6 MPa.

We found that the cluster wall residence length scales with the mean particle diameter, but is independent of operational conditions. We also observed that the Nusselt number at the wall is proportional to the cluster fractional wall coverage, and the square root of the mean cluster solid volume fraction and the ratio of characteristic times mentioned earlier.

INTRODUCTION

Recent models of heat transfer to the wall of circulating fluidized bed risers have underlined the central role played by particle clusters (Lints and Glicksman, 1993b). In this flow regime, the suspension consists of an ascending dilute core surrounded by a descending annulus near the wall. In the annulus, the suspension partly condenses into denser clusters separated from the wall by a thin gas film of order the mean particle diameter (Glicksman, 1997). The clusters generally dominate the convective heat exchange with the wall because of their relatively high solid volume fractions and heat capacity.

Accordingly, Lints and Glicksman (1993a) suggested that the rate of convective heat exchange at the wall scales with the ratio of two characteristic times. The first is the time necessary for cluster particles to cool by conduction through the gas layer. The second is the residence time spent by clusters at the wall, which combines the clusters' residence length and mean descending velocity.

To verify the insight of Lints and Glicksman (1993a), we measured the convective heat transfer rate with a non-invasive, constant temperature probe capable of recording simultaneously the volume fraction and heat flux at the wall. The principle of our experiments was to maintain hydrodynamic similarity in the fully-developed upper region of a circulating fluidized bed riser, while conducting heat transfer measurements with gas and solid materials of different thermal properties.

We maintained hydrodynamic similarity among different experiments by matching the reduced set of four dimensionless parameters proposed by Glicksman, et al (1993),

$$Fr^2/L = u^2 / gD \,, \tag{1}$$

$$M/R = G/\rho_s u \,, \tag{2}$$

$$V = u/u_t \,, \tag{3}$$

and

$$R = \rho_s / \rho \,, \tag{4}$$

where ρ and ρ_s are the material density of the gas and solids, respectively; u is the superficial gas velocity; G is the overall solid flux; g is the acceleration of gravity; D is the riser diameter; and u_t is the terminal velocity of the particles. The Froude number Fr and solid loading M are operational parameters. R is the density ratio. The dimensionless size $L = D/\varphi d_s$ is a measure of the size of the unit that combines the sphericity φ and the mean Sauter diameter d_s. Bricout and Louge (2000) provide a summary of this approach in these Proceedings. Although this similarity is valid when the drag on solid particles conforms either to the viscous or to the inertial limit, they showed that it can also succeed in the intermediate regime, at least in the upper region of the riser where the flow is nearly fully-developed. Through the reduced scaling, our experimental conditions were then analogous to a coal combustor pressurized to 0.6 MPa.

By inspecting data from several investigators, we also established that the cluster descending velocity scales with the square root of the particle diameter and the gravitational acceleration (Griffith and Louge, 1998). Finally, we recorded the cluster residence length using a new thermal marking technique.

We begin with a summary of the thermal scaling of Lints and Glicksman (1993a). We then briefly describe our experimental approach and discuss its results.

THERMAL SCALING

Lints and Glicksman (1993a) described the convective thermal exchange at the wall of a circulating fluidized bed as two parallel processes leading to an overall heat transfer coefficient h,

$$h = f_h \, h_c + (1 - f_h) \, h_g \,. \tag{5}$$

The first is an exchange characterized by the coefficient h_c involving particle clusters covering the fraction f_h of the wall surface. The second has coefficient h_g and involves an emulsion around clusters that is largely devoid of particles. Lints and Glicksman then modeled the heat transfer to clusters as two processes in series, namely a conduction through the thin gas film of thickness δ followed by a convective exchange to the clusters with coefficient h_H,

$$\frac{1}{h_c} = \frac{\delta}{k} + \frac{1}{h_H} \; . \tag{6}$$

To capture h_H, Lints and Glicksman borrowed from the model of Mickley and Fairbanks (1955) for bubbling beds. In that model, the authors treated the emulsion as a semi-infinite homogeneous medium and adopted the classical heat flux expression for transient conduction into a semi-infinite slab. Then, after invoking effective thermal properties for the emulsion phase and time averaging, they derived the form of the wall heat transfer coefficient,

$$h_H \sim \sqrt{\frac{k_e \;\rho_s\; c_p\; \nu_c}{\tau_c}} \; , \tag{7}$$

where k_e is the effective conductivity of the emulsion phase, τ_c is its average contact time with the wall, ν_c is its solid volume fraction and ρ_s and c_p are, respectively, the material density and specific heat of the solids.

Three assumptions lead to a simpler scaling of the overall heat transfer coefficient. First, because the conductivity of the solid material is much greater than that of the interstitial gas, the effective cluster conductivity is governed by the gas conductivity k. Consequently, it is appropriate to substitute k for k_e in Eq. (7). Then, because Ebert, et al (1993) measured a smaller gas convective component than its solid counterpart, we neglect the second term in Eq. (5). Finally, we also assume that the convective transfer to the clusters dominates the conduction through the thin gas layer, $(1/h_H >> \delta/k)$. Using these simplifications in Eqs. (5) to (7), we expect that the Nusselt number scales as

$$Nu_d = \frac{h\; d_s}{k} \sim f_h \sqrt{\frac{\tau_p\; \nu_c}{\tau_c}} \; , \tag{8}$$

where $\tau_p = \rho_s\; c_p\; d_s^2/k$ is a characteristic time for the heating of a particle of diameter d_s.

To verify this scaling experimentally, we must record values of h, f_h, ν_c and τ_c. We interpret ν_c as the mean cluster volume fraction and τ_c as the cluster residence time at the wall. We outline the corresponding measurement techniques in the next section.

INSTRUMENTATION

Our experiments were conducted in the circulating fluidized bed riser of 0.2 m diameter and 7 m height sketched by Bricout and Louge (2000) in the present Proceedings. For all experimental conditions, the static pressure gradient was uniform around our instruments located mid-height through the riser. The unique ability of this facility is to recycle any desired mixture of inert fluidization gases near ambient temperature and pressure, thus allowing us to adjust the dimensionless numbers characterizing the fluid dynamics and heat transfer of the suspension (Louge, et al., 1999).

We recorded the instantaneous overall heat transfer coefficient and volume fraction at the wall using a non-invasive instrument that combines a capacitance sensor with a small platinum coil maintained at constant temperature by a rapid anemometer bridge circuit (Griffith, Louge and Mohd-Yusof, 2000). Figure 1 is a sketch of the probe tip. Guard heaters wrapped around the vessel minimized effects of conduction losses and thermal entry length.

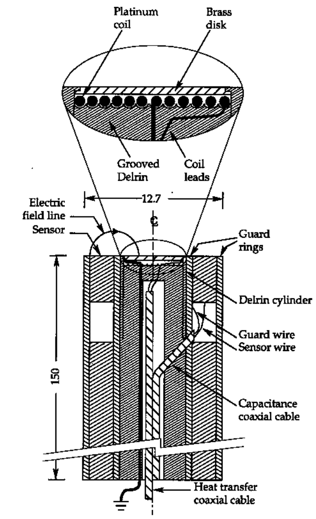

Fig. 1. Sketch of the combined capacitance and heat transfer probe tip. Dimensions are in mm.

We extracted the fractional wall coverage f_h and the mean cluster volume fraction ν_c from instantaneous records of the capacitance probe. To that end, we identified clusters as portions of the signal that exceeded the time-average solid volume fraction. We then defined f_h as the fraction of the time when those clusters occurred and ν_c as the mean volume fraction during those events.

We interpreted the cluster residence time τ_c as a ratio of the mean cluster residence length at the wall λ and the mean descending cluster velocity u_{cl}. Griffith and Louge (1998) determined a correlation for the latter by inspecting available literature data. They found

$$u_{cl} \approx 36 \sqrt{gd} \,, \tag{9}$$

where g is the gravitational acceleration.

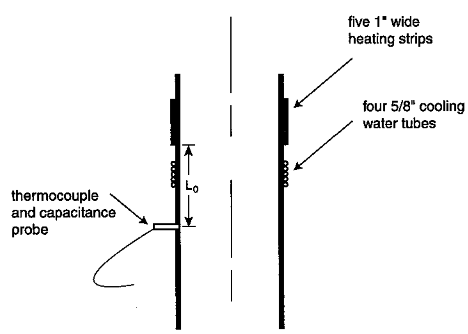

Fig. 2. Sketch of the thermal marking technique.

It remained to measure λ, the average length traveled by clusters in contact with the wall. To that end, we developed a thermal marking instrument consisting of a combined thermocouple and capacitance probe located beneath an axisymmetric heating region composed of five heating strips and a bank of cooling tubes (Fig. 2). The thermocouple was inserted through the central grounded surface of the capacitance probe and it protruded a mere 300μm into the riser (Griffith, 2000). The capacitance wall probe was similar to the one used for the heat transfer measurements.

The heating region was designed to warm up descending clusters that contact the wall above an adjustable height L_0 from the combined probe. The cooling tubes ensured that clusters arriving at the wall beneath them did not get heated. A visual inspection of the simultaneous signals from the thermocouple and the capacitance probe revealed the fraction f of heated clusters passing in front of the probe (Fig. 3). The fraction was obtained by identifying individual clusters occurring at a typical rate of two per second, and by recognizing those with excursions of the thermocouple temperature above a threshold 0.4°C higher than the baseline.

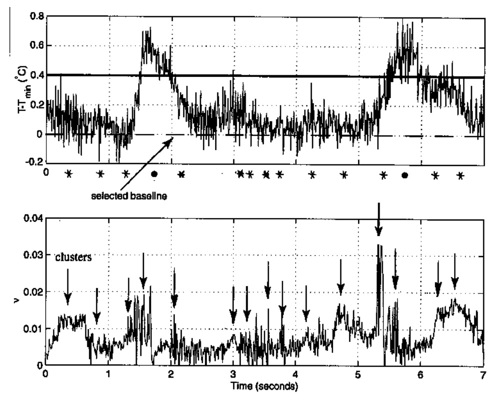

Fig. 3. Simultaneous records of solid fraction (bottom) and temperature fluctuation (top) from the capacitance-thermocouple probe with a spacing L_0 = 86 cm and a suspension of 102 μm glass beads with the conditions Fr^2/L = 5.5, u/u_t = 5.8, M/R = 0.0015 and R = 1680. Vertical arrows indicate recognizable clusters. Clusters with temperature rising above the threshold are deemed to be "hot" and denoted by circles. Clusters below the threshold are "cold" and denoted by a star.

As Fig. 4 illustrates, we repeated this measurement at several different values of L_0 for each experimental condition. To analyze the results for the fraction f of heated clusters, we assumed that the clusters, the probe and the heater are points, that the clusters descend at a constant speed, that their flux of arrival at the wall is uniform, and that the heating is instantaneous. We then defined the normalized probability distribution function (PDF) of cluster residence length $f_r(\ell)$ such that the fraction of clusters with residence length in the range $[\ell, \ell+d\ell]$ is $f_r(\ell)d\ell$. Then, if the probe and heaters are separated by the distance L_0, the observed fraction of heated clusters is

$$f(L_0) = \frac{\int_{L_0}^{\infty}\left[\int_z^{\infty} f_r(\ell)d\ell\right]dz}{\int_0^{\infty}\left[\int_z^{\infty} f_r(\ell)d\ell\right]dz} \,. \tag{10}$$

The shape of the observed $f(L_0)$ suggests that the PDF of residence lengths is exponential,

$$f_r(\ell) = (1/\lambda)\exp(-\ell/\lambda)\,, \tag{11}$$

which yields

$$f(L_0) = \exp(-L_0/\lambda) \ . \tag{12}$$

Using this expression, it was then straightforward to extract a characteristic cluster residence length λ from the observed function $f(L_0)$.

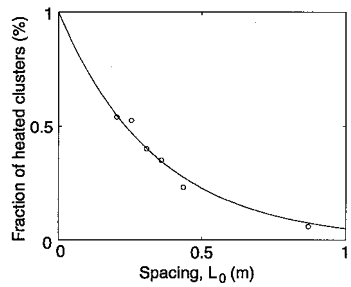

Fig. 4. Observed fraction of heated clusters versus spacing L_0 for the conditions of Fig. 3.

EXPERIMENTS AND RESULTS

Table 1 summarizes the experimental mixtures and conditions. All mixtures shared the same value of R = 1680. The principle of the first three experiments was to maintain hydrodynamic similarity in the upper riser using the reduced scaling parameters of Glicksman, et al (1993), while conducting heat transfer measurements with gas and solid materials of different thermal properties.

Table 1 - Operating conditions and residence length

experiment	solids			gases	dimensionless numbers				
	material	d_s (μm)	L		Fr^2/L	M/R	u/u_t	Ar	λ (m)
1	glass	102	1930	50% CO_2	5.5	0.0015	5.8	153	0.32
				50% air	5.4	0.0060	5.8		0.26
					12.2	0.0061	8.7		0.32
2	plastic	104	1902	67% air	5.4	0.0015	5.8	37	0.46
				33% He	5.5	0.0060	5.8		0.25
					12.1	0.0060	8.6		0.31
3	glass	107	1840	60% He	5.5	0.0015	5.8	140	0.29
				16% SF_6	5.6	0.0059	5.9		0.30
				24% CO_2	12.1	0.0061	8.6		0.30
4	glass	64	3100	50% CO_2	3.3	0.0015	9.7	37	0.20
				50% air	3.4	0.0061	9.9		0.19
					7.3	0.0061	14.5		0.20

The fourth experiment was designed to evaluate how the cluster residence length scaled with particle diameter. To that end, it shared with experiment two the same hydrodynamic parameters from the complete similitude of Louge, at al (1999), except for the dimensionless size L. Thus, experiments two and four had identical values of Fr, M, R and the Archimedes number $Ar = \rho_s \rho (\varphi d_s)^3 g / \mu^2$, where μ is the viscosity of the gas.

As Fig. 5 shows, the characteristic cluster residence length scaled with the particle diameter, and the scaling was remarkably insensitive to operating conditions, in agreement with the observations of Noymer (1997).

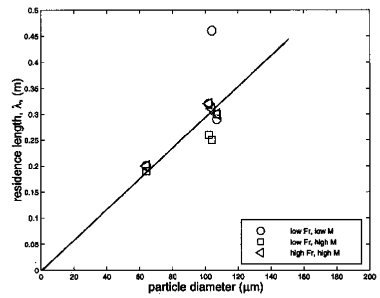

Fig. 5. Characteristic cluster residence lengths λ versus particle diameter from experiments two (d_s = 104 μm) and four (d_s = 64 μm).

In experiments one and two, we held the product $\tau_p u_{cl}/d_s$ constant, while in experiment three, we varied this number by roughly a factor of two. Thus, because λ grows with d_s, we could test Eq. (8) with mixtures providing sufficient breadth in the parameters involved with the scaling. As Fig. 6 shows, the Nusselt does conform to the expected dependence.

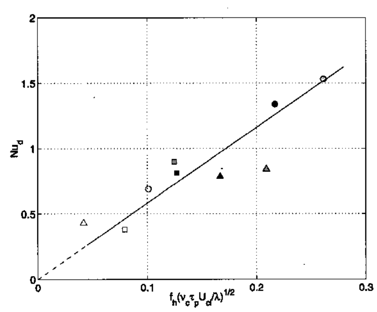

Fig. 6. Nusselt number based on particle mean Sauter diameter versus the product $f_h(\nu_c \tau_p u_{cl}/\lambda)^{1/2}$. White, gray and black symbols are, respectively, for conditions of low Fr and low M, low Fr and high M, and high Fr and high M (Table 1). Circles, triangles and squares represent experiments one, two and three, respectively.

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