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BED-TO-WALL HEAT TRANSFER CHARACTERISTICS IN A CIRCULATING FLUIDIZED BED

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Abstract – The bed-to-wall heat transfer coefficients were measured in a circulating fluidized bed of FCC particles ($\bar{d}_p$= 65 μm). The effects of gas velocity (1.0-4.0 m/s), solid circulation rate (10-50 kg/m²s) and particle suspension density (15-100 kg/m³) on the bed-to-wall heat transfer coefficient have been determined in a circulating fluidized bed (0.1 m-ID×5.3 m-high). The heat transfer coefficient strongly depends on particle suspension density, solid circulation rate, and gas velocity. The axial variation of heat transfer coefficients is a strong function of the axial solid holdup profile in the riser. The obtained heat transfer coefficient in terms of Nusselt number has been correlated with the pertinent dimensionless groups

Key words: *Heat Transfer Coefficient, Circulating Fluidized Bed, Particle Convective Heat Transfer, Heat Transfer Length, Suspension Density*

INTRODUCTION

In recent years, circulating fluidized beds (CFB) have been extensively used in coal combustion and gas-solid reactions in chemical industries. For proper design of CFB reactors or boilers, it is important to know the effect of design and operating variables on the bed-to-wall heat transfer coefficient. Numerous research works have been carried out to determine the heat transfer characteristics in conventional bubbling fluidized beds but, studies on heat transfer in circulating fluidized beds are relatively sparse.

It has been known that the bed-to-wall heat transfer coefficient in CFBs depends on the particle suspension density that is a function of particle size, gas velocity, and solid recycle rates. The heat transfer is mainly governed by the particle convection in a CFB. Based on the literature data of heat transfer coefficients with different heat transfer surface, it can be seen that the heat transfer coefficient also depends on the heat transfer length [Basu and Nag, 1987; Glicksman et al., 1988; Wu et al., 1989a; Nag and Moral, 1990; Han, 1992].

In the present study, the effects of gas velocity, solid circulation rate and particle suspension density on the bed-to-wall heat transfer coefficient in a circulating fluidized bed have been determined. Also, the effect of heat transfer length on the particle convective heat transfer coefficient is determined based on the present and previous studies.

EXPERIMENTAL

Experiments were carried out in a transparent Plexiglas column of 0.1 m-ID×5.3 m-high at room temperature as shown in Fig. 1. The solid particles used in this study were fluid cracking catalyst (FCC) particles (Table 1) which were supported on a perforated plate distributor which contained 19 holes (6.0 mm-ID) with triangular pitch and covered with a 250 mesh screen. The distributor was situated between the main column section and an air box (0.1 m-ID×0.2 m-high) into which air was fed to the column through a pressure regulator, an oil filter and a calibrated flowmeter. The entrained particles from the riser were collected by the primary and secondary cyclones and stored in a hopper. At a given fluidizing air velocity, solid particles were fed from the hopper into the riser through a rotary valve. A slide valve was installed in the return leg to measure the solid circulation rate. The gas velocity (U_g) and the sol-

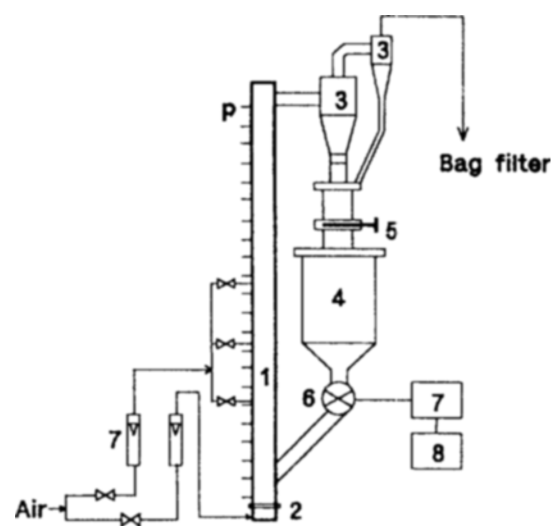

Fig. 1. Schematic diagram of the CFB.

1. Riser	6. Rotary valve
2. Distributor	7. Flow meter
3. Cyclone	8. DC motor
4. Hopper	9. Speed controller
5. Slide valve	P. Pressure taps

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Table 1. Properties of FCC

Properties	
Mean diameter [μm]	65
Apparent density [kg/m³]	1720
Thermal conductivity [W/mK]	0.95
Heat capacity [J/kg K]	874.5

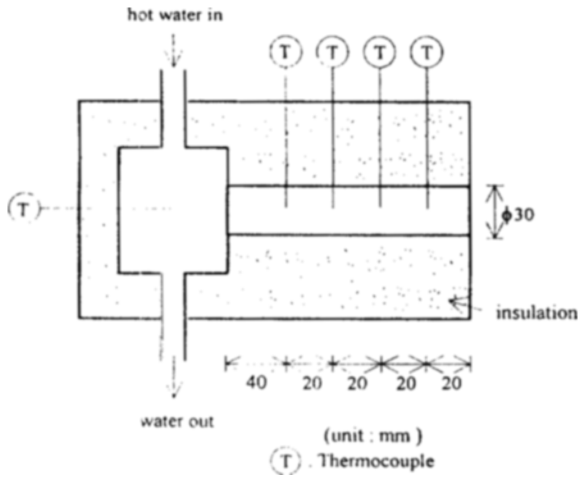

Fig. 2. Dimension of heat flux meter.

id circulation rate (G_s) were varied in the range of 1.0-4.0 m/s and 10-50 kg/m²s, respectively. Pressure taps were mounted flush with the wall of the column and connected to pressure transducers from which pressure signals were stored in a data acquisition system. When the system reached steady state, pressure drop and temperature across the probe were measured. Since the pressure gradient ($\Delta P/\Delta L$) has a linear relationship with the solid concentration [Arena et al., 1986], the suspension density can be determined from the time averaged pressure drop gradient by the following relationship.

$$\rho_{sus} = \varepsilon_s \rho_s + (1 - \varepsilon_s)\rho_g \cong (\Delta P/\Delta L)/g \quad (1)$$

The details of the heat flux meter used in this study is shown in Fig. 2. Five heat flux meters were mounted flush with the wall of the column at 0.9, 1.7, 2.3, 3.0 and 3.7 m above the distributor to determine the axial variation of heat transfer coefficients. The heat flux meter was made of carbon steel rod (0.03 m-OD × 0.12 m-long) where four T-type (copper-constantan) thermocouples were placed along the rod at 0.02 m intervals. The other end of the rod was in contact with circulating hot water (Fig. 2). Water temperature in a hot water tank was controlled by a temperature controller in the range of 88-92°C and measured by a thermocouple (T-type). Two pressure taps were mounted across the heat flux meter and the local particle suspension density was determined from the bed pressure drop. The heat flux meter was insulated to attain one-dimensional heat conduction in the steel rod which was confirmed by a linear temperature profile along the rod. The surface temperature of the meter in contact with the solids in the bed (T_w), was estimated by the linear extrapolation of the temperature profile along the rod [Chen and Chen, 1992]. The bed temperature was measured by a thermocouple (T-type) which

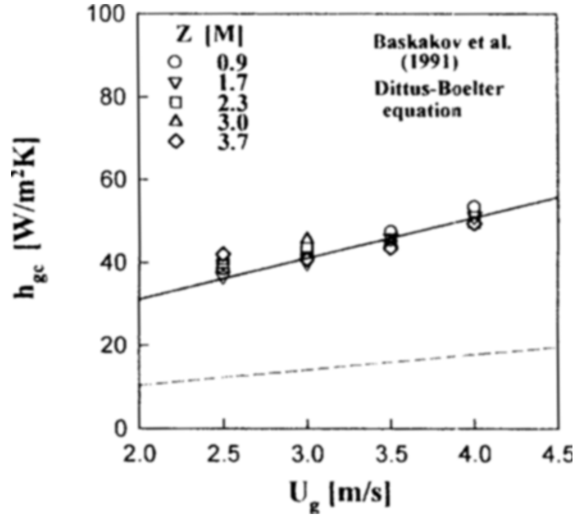

Fig. 3. Comparisons of the local gas convective heat transfer coefficient with the reported correlations.

was installed inside the bed.

The heat flux (q) from the rod to the fluidized bed was obtained from the temperature gradient (dT/dx) by the Fourier's law of heat conduction as

$$q = -k(dT/dx) \quad (2)$$

The heat transfer coefficients (h_w) are determined by the following equation from the measured heat flux as

$$h_w = q/(T_w - T_{bed}) \quad (3)$$

RESULTS AND DISCUSSION

1. Axial Variations of Heat Transfer Coefficients

To evaluate the present experimental technique for measuring the bed-to-wall heat transfer coefficient, the heat transfer coefficient in the bed of air flow only is shown in Fig. 3 where the obtained coefficient is compared with the calculated values from the Dittus-Boelter equation [Holman, 1986] for gas convection only.

$$Nu = 0.023\, Re^{0.8} Pr^{0.3} \quad (4)$$

This equation can be applied only to the fully developed flow condition of constant fluid property without the effects of hydrodynamic and thermal entry on heat transfer coefficient. As can be seen, the measured heat transfer coefficients are higher than the predicted ones (dotted line) from Eq. (4) due to the short vertical length of heat flux probe used in this study. When the vertical length of the heat transfer surface is short, the obtained heat transfer coefficients are higher than those from the longer surfaces since the thermal boundary layer is not fully developed across the short heat transfer surface. Recently, Baskakov et al. [1991] presented a correlation to predict the heat transfer coefficient in terms of Nusselt number (Nu) as a function of vertical length of heat transfer surface as

$$Nu = 0.0214(Re_p^{0.8} - 100)Pr^{0.4}[1 + (D_t/L_H)^{2/3}] \quad (5)$$

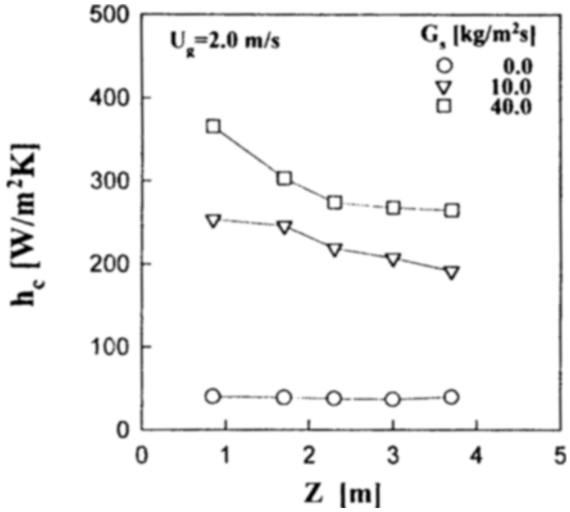

Fig. 4. Local heat transfer coefficient along the riser height.

where Re_p, Pr, D_t and L_H are particle Reynolds number, Prandtl number, column diameter and heater length, respectively.

As can be seen in Fig. 3, the agreement is satisfactory between the calculated (solid line) values from Eq. (5) and the experimental values which may reflect the present experimental technique is reliable one. Also, the heat transfer coefficients increase with air velocity due to the increase of turbulence in the gas stream.

The axial variations of heat transfer coefficient with different solid circulation rates are shown in Fig. 4. In a circulating fluidized bed, the total bed-to-wall heat transfer coefficient (h_t) could be approximated as the sum of three separate, additive components accounting for gas convection (h_{gc}), convective transfer due to particles (h_{pc}), and radiation (h_{rad}) components [Grace, 1986] as

$$h_t = h_{gc} + h_{pc} + h_{rad} \tag{6}$$

where the radiative component can be neglected in this study [Wu et al., 1989b]. Therefore, the heat transfer coefficient in this study (Fig. 4) may represent the convective heat transfer coefficient (h_c) composed of gas (h_{gc}) and particle convection (h_{pc}) components. As can be seen in Fig. 4, the local heat transfer coefficient decreases with the bed height. In the preliminary study of gas convective heat transfer measurement, it was found that gas convective heat transfer coefficient is independent with the bed height. Therefore the heat transfer coefficient decreases with the bed height due to the decrease of heat transfer caused by particle convective component. This axial variation of heat transfer coefficients may due to the variation of particle suspension density in a circulating fluidized bed. Li and Kwauk [1980] and Hartge et al. [1986] reported that axial solid concentration or suspension density changes with the riser height having S-shape profile. Therefore, the axial variations of heat transfer coefficients exhibit an existence of axial variation of solid concentration in the circulating fluidized beds.

In comparison of heat transfer coefficients in the bed of particles (G_s=10.0 or 40.0 kg/m²s) and without particles (G_s=0), it can be noticed that the presence of particles in gas flow augments the heat transfer greatly between the wall and gas-solid

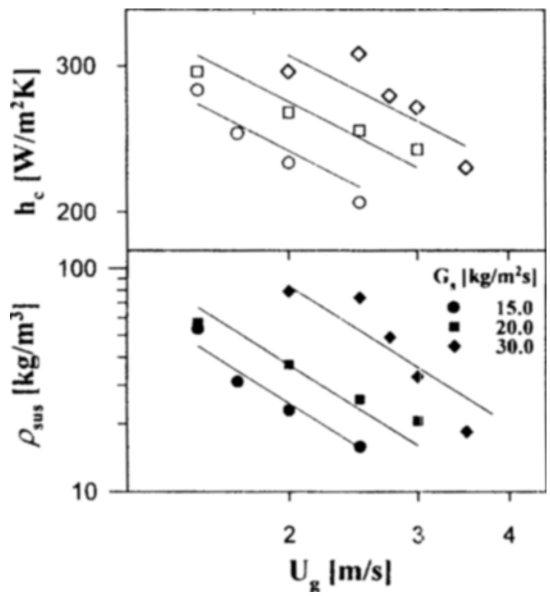

Fig. 5. Effect of gas velocity on heat transfer coefficient and suspension density at different solid circulation rates.

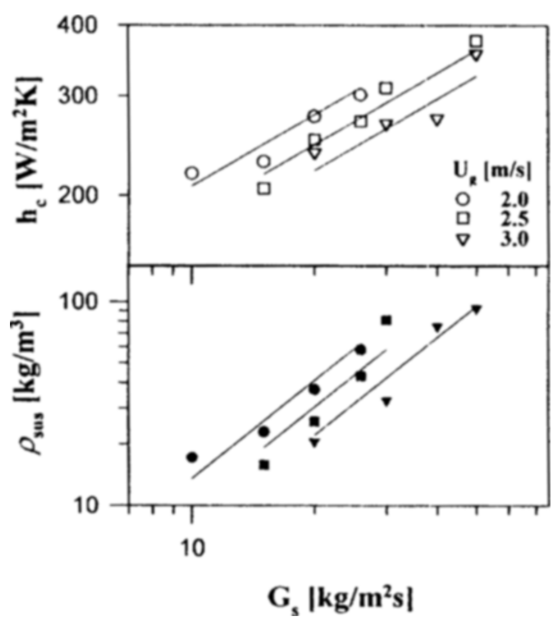

Fig. 6. Effect of solid circulation rate on heat transfer coefficient and suspension density at different gas velocities.

suspension since particle suspension has higher volumetric heat capacity and disturbs the viscous sublayer effectively [Han, 1992].

2. Effects of Gas Velocity (U_g) and Solid Circulation Rate (G_s)

The effects of U_g and G_s on the heat transfer coefficient and suspension density are shown in Figs. 5 and 6. As shown in Fig. 5, the particle suspension density decreases with increasing U_g at a given G_s and the corresponding heat transfer coefficients also decrease. In the gas convective heat transfer, the heat transfer coefficient increases with increasing U_g due to the enhanced turbulence in gas flow. However in a circulating fluidized bed, in spite of the increased portion of gas convective heat transfer at higher gas velocity the total heat trans-

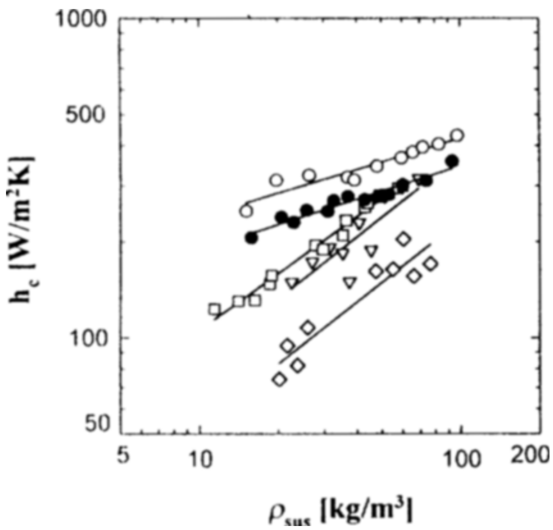

Fig. 7. Effect of heat transfer surface on the heat transfer coefficients (symbols are given in Table 2).

fer coefficient (h_r) decreases with increasing U_g (Fig. 5). This may indicate that the contribution of gas convective component to the total heat transfer coefficient is comparatively smaller than the particle convective component at the moderate temperature ranges [Grace, 1986]. On the other hand, at a given U_g, particle suspension density increases with increasing G_s and consequent increase in heat transfer coefficients. Therefore, gas velocity and solid circulation rate are the major operating parameters to determine particle suspension density and heat transfer due to particle convection in circulating fluidized beds.

3. Effects of Suspension Density and Probe Length

The heat transfer coefficients as a function of particle suspension density with different length of heat transfer probe of the present and previous studies [Basu, 1990; Chen and Chen, 1992; Kobro and Breteton, 1986; Wu et al., 1986b] are shown in Fig. 7 where the particle convective heat transfer coefficients increase with particle suspension density. When the solid particles contact with the heat transfer surface, transient heat conduction may take place that is the dominating mode of heat transfer between the fluidized bed and the wall. Therefore higher suspension density will result in a higher frequency of particle bombardments against the wall and consequent increase in heat transfer [Han, 1992]. Heat transfer from the particle suspension to the bed wall is considered as the combination of conduction by the down flow of particle clusters near the wall and convection by the upflowing gas containing the dispersed particles in the core of the bed [Basu and Nag, 1987]. Thus, the conductive heat transfer from the particle cluster is higher than the convective heat transfer from the dispersed phase.

The bed-to-wall heat transfer coefficient is higher in the denser bed than that in the leaner bed since the fraction of the wall is covered by clusters is larger in the former bed than that in the latter bed [Basu and Fraser, 1991]. Furthermore, the heat transfer coefficients with smaller particles are higher than those with the larger ones as shown in Fig. 7 since the smaller particles have more contact points per unit surface area than the larger ones. As can be seen in Fig. 7, the slopes of the lines

Table 2. A summary of experimental conditions with different length of heat transfer surfaces

Investigator	Symbol	Particle type	Particle size [μm]	Particle density [kg/m³]	Probe length [m]
Kobro and Brereton [1986]	◇	sand	170	2630	0.1
Wu et al. [1986b]	□	sand	171	2650	0.01
Basu [1990]	▽	sand	130	2630	0.0254
Chen & Chen [1992]	○	FCC	71	1800	0.0254
This study	●	FCC	65	1720	0.03

are different with two types of particle such as the Geldart types A (FCC) and B (sand). Since different types of particle having different thermal properties and exhibit different fluidization quality, the rate of increase in h_c with suspension density is higher in the bed of sand particles than that in the bed of FCC particles. The details of all the symbols in Fig. 7 are given in Table 2.

Regarding on the effect of probe length on the heat transfer coefficient, the heat transfer coefficients of Kobro and Brereton [1986] are lower than those of Wu et al. [1989b] in the bed of similar size of sand particles since the former employed longer heat transfer probe than that of the latter. When the heat transfer surface is long, the first layer of particles will stay longer on the wall and cool down at the temperature of heat transfer surface. Thus, the increase of thermal resistance of these particles leads to decrease in heat transfer coefficient. For example, Kobro and Brereton [1986] obtained h_c value of 100 W/m² K with the probe length of 0.1 m whereas, Wu et al. [1989b] reported h_c value of 200 W/m² K with probe length 0.01 m with the same particle size at a constant suspension density (30 kg/m³). Therefore, probe length produces significant difference in the heat transfer coefficient since shorter probe has shorter contact time of clusters on the wall which reduce the thermal resistance of particle clusters.

4. Correlation

The obtained particle convective heat transfer coefficient in terms of Nusselt number of the present and previous studies [Basu, 1987; Cho, 1994; Dou, 1991; Wu, 1987] has been correlated with the pertinent dimensionless groups. In general, the convective heat transfer coefficient in terms of Nusselt number in CFBs can be affected by the operating variables of U_g, G_s, d_p and thermal properties of gas and solids. The bed-to-wall heat transfer in a CFB is a strong function of particle suspension density which is varied with the riser height. Therefore, information of particle suspension density along the riser height is needed to estimate heat transfer in CFBs. Recently, Namkung et al. [1994] proposed a correlation of particle suspension density in the present experimental equipment with the solid holdup data of their study and the literature data [Bai et al., 1992; Arena et al., 1986; Rhode and Geldart, 1986] as

$$\frac{\varepsilon_g}{\varepsilon_s} = 0.047\left(\frac{u_g^2}{gd_p}\right)^{0.41}\left(\frac{G_s}{\rho_s u_g}\right)^{-1.18}\left(\frac{D_t}{d_p}\right)^{-0.53} \exp\left[1.72\left(\frac{Z}{H_t}\right)\right] \tag{7}$$

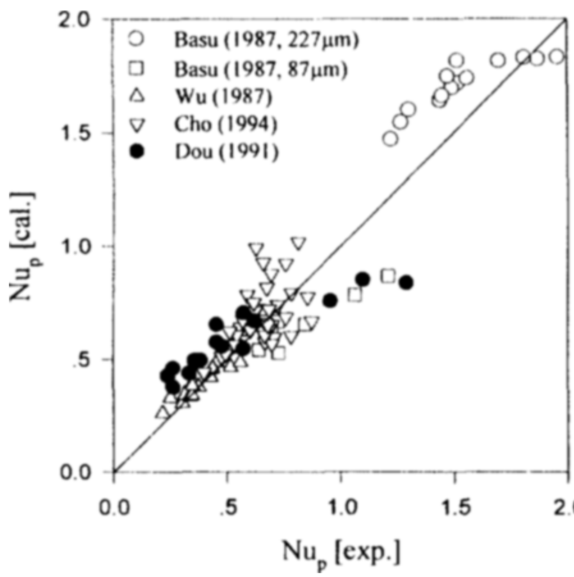

Fig. 8. Comparison of the experimental and calculated values of Nusselt number.

As can be seen, solid phase holdup or suspension density is correlated as a function of Froude number, the ratios of solid to gas velocities and column diameter to particle size and the dimensionless riser height. Since the heat transfer coefficient exhibits linear relation to the suspension density, the present heat transfer coefficients have been correlated with the same parameters in Eq. (7) with cooperating the effect of heat transfer probe length as

$$Nu_p = 3978\left(\frac{U_g^2}{gd_p}\right)^{-0.227}\left(\frac{G_s}{\rho_s U_g}\right)^{0.270}\left(\frac{D_t}{d_p}\right)^{-0.472}\left(\frac{d_p}{L_H}\right)^{0.254} \exp\left[-0.535\left(\frac{z}{H_t}\right)\right] \tag{8}$$

with a correlation coefficient of 0.91 and a standard error of estimate of 16.8%. The goodness of fit between the experimental and calculated values of Nusselt number from Eq. (8) is shown in Fig. 8. As can be seen, the proposed correlation can predict the bed-to-wall heat transfer coefficient in the CFB riser with a reasonable accuracy.

CONCLUSIONS

Based on the present and previous studies of heat transfer coefficients in circulating fluidized beds, the following conclusions can be made. The bed-to-wall heat transfer coefficient increases with solid circulation rate and decreases with gas velocity. The axial variation of heat transfer coefficients exhibits the same trend of the axial solid concentration profile in the bed. In the bed, smaller particles produce higher heat transfer coefficient than the larger ones due to higher contact points on the heat transfer surface. The shorter vertical length of heat transfer probe exhibits higher heat transfer coefficient than the longer one at the same suspension density and particle size. A correlation is proposed to predict particle convective heat transfer coefficient in circulating fluidized beds.

NOMENCLATURE

C_{pg} : heat capacity of fluidizing gas [J/kgK]
C_{pp} : heat capacity of particles [J/kgK]
d_p : particle diameter [m]
D_t : column diameter [m]
dT/dx : temperature gradient within the probe of heat flux meter [K/m]
g : gravitational acceleration [m/s^2]
G_s : solid circulation rate [kg/m^{2}s]
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]
h_{rad} : radiative heat transfer coefficient [W/m^{2}K]
h_t : total heat transfer coefficient [W/m^{2}K]
h_w : bed-to-wall heat transfer coefficient [W/m^{2}K]
k : thermal conductivity of the heat flux meter [W/mK]
k_g : thermal conductivity of gas [W/mK]
l : characteristic length [m]
L_H : the vertical length of heat transfer surface [m]
Nu : Nusselt number (h l/kg) [-]
Nu_p : particle Nusselt number (h d_p/kg) [-]
Pr : Prandtl number ($C_p\mu/k$) [-]
q : heat flux from the surface of heat flux meter to bed [W/m^2]
Re : Reynolds number ($D_tU_g\rho_g/\mu$) [-]
Re_p : Reynolds number based on particle diameter ($d_pU_g\rho_g/\mu$) [-]
T : temperature [K]
T_{bed} : bed temperature [K]
T_w : surface temperature of heat flux probe in contact with bed [K]
U_g : superficial gas velocity corresponding to total air flow rate [m/s]
U_t : particle terminal velocity [m/s]
x : distance along the heat flux probe [m]
Z : distance from the distributor [m]

Greek Letters

$\Delta P/\Delta L$: pressure drop [kg/m^3]
ε : gas holdup [-]
ε_s : solid holdup [-]
μ_g : gas viscosity [kg/ms]
ρ_g : gas density [kg/m^3]
ρ_s : solid density [kg/m^3]
ρ_{sus} : suspension density [kg/m^3]

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