Int. J. Heat Mass Transfer. Vol. 29, No. 3, pp. 487–489, 1986
Printed in Great Britain

0017-9310/86 $3.00 + 0.00

TECHNICAL NOTES

A model for heat transfer in circulating fluidized beds

D. SUBBARAO and P. BASU
Centre for Energy Studies, Technical University of Nova Scotia, Halifax, Canada B3J 2X4

(*Received* 28 *March* 1985 *and in final form* 3 *September* 1985)

INTRODUCTION

GOOD HEAT transfer characteristics of dense fluidized beds are mainly due to the bubbling phenomenon. However, the bubbling phenomenon is also responsible for gas bypassing and poor gas–solid contacting. Yerushalmi *et al.* [1] reviewed gas–solid contacting at high gas velocities where bubbles break down, leading to a turbulent bed or a transport/fast bed. The onset of a turbulent bed is characterized by the dispersion of particles in a continuous gas phase. For gas velocities beyond the 'transport/blow out velocity', particles get totally entrained. Recycling of the entrained particles to the bottom of the bed provides a method to bring gas into contact with a batch of solids and such beds were named as 'fast beds' by Yerushalmi *et al.* [1]. Even for turbulent beds, the recirculation of elutriating solids can be advantageous. There are indications that gas–solid contact is better under the turbulent/fast circulating bed regime. Coal combustion, coal gasification, and precalcination in cement manufacture are a few technologies which employ circulating fluidized bed processing. For these various processes, the fluidized bed is an attractive choice mainly due to better heat transfer characteristics and the capability of handling solids easily.

Only a few heat transfer measurements on turbulent/fast bed regimes or transport lines are reported to date [3–9]. A few of these were on wall/jacket heat transfer while others were on heat transfer from a probe immersed in the bed. The experimental conditions and correlations of various investigations are summarized in Table 1. Measurement of the recirculation rate of solids is difficult; therefore some of the investigators did not attempt this. Instead, bed density was measured and heat transfer coefficients were found to be mainly a function of bed density. Dependence of heat transfer coefficient on other parameters is still not certain. Mickley and Trilling [3] observed that heat transfer coefficients decrease with increase in particle size and are independent of column diameter while Danziger [6] reached the opposite conclusion. Fraley *et al.* [9] correlated that heat transfer coefficients increase with increase in column diameter.

In the present work an attempt is made to develop an understanding into the process of heat transfer considering the co-current gas–solid flow behaviour in terms of a cluster model for lean beds developed by Subbarao [10].

THE MODEL

It has been recognized for some time now that in co-current gas–solid flow in turbulent/fast circulating beds, the particles agglomerate to move as clusters in the flowing gas [1]. As this clustering of particles simultaneously produces voids free of particles (bubbles), Subbarao [10] visualized such beds to consist of clusters and bubbles. Also, recognizing that each cluster will be associated with one void/bubble and assuming that the frequency of clusters and bubbles is the same, cluster diameter for co-current gas–cluster flow was obtained from material balance as

$$D_c = \left(\frac{W}{\rho_p(1-\varepsilon_c)U_0}\right)^{1/3} D_b. \tag{1}$$

Bubble size is assumed to grow to its maximum stable size or to pipe size, whichever is smaller. Under conditions of slugging, $\{(U-U_{mf})/[0.35(gD_t)]^{0.5}\} > 0.2$, bubble size is assumed to be pipe size itself [13].

Such clusters and bubbles at bed temperature contact heat transfer surface at a uniform temperature. Consider a unit heat transfer surface. At any given time, δ_c fraction of heat transfer surface is exposed to clusters and $(1-\delta_c)$ fraction is exposed to bubbles. Then the area-averaged heat transfer coefficient can be written as

$$h = h_c\delta_c + h_b(1-\delta_c). \tag{2}$$

The components h_c and h_b are the time-averaged heat transfer coefficients for clusters and bubbles, respectively. Consider a cluster of size D_c with an average axial velocity U_c parallel to the heat transfer surface. Also consider a heat transfer surface the size of a cluster. This particular area is exposed to a cluster

NOMENCLATURE

c	specific heat
D	diameter
D_{pr}	diameter of the probe
D_t	diameter of the tube
g	acceleration due to gravity
h	heat transfer coefficient
k	thermal conductivity
T	contact time for heat transfer
U_0	superficial gas velocity
U_t	terminal velocity
U_c	cluster velocity
U_{br}	bubble/slug velocity
W	solids mass velocity.

Greek symbols

δ_c	cluster fraction
ε	porosity
ε_{mf}	porosity at minimum fluidization velocity
μ	viscosity
ρ	density
ρ_m	mean bed density.

Subscripts

b	bubble
c	cluster
g	gas
p	particle.

Table 1

Ref.	D_t (m)	D_{pr} (m)	$D_p \times 10^{-2}$ (m)	ρ_p (kg m^{-3})	W (kg m^{-2} s^{-1})	U (m s^{-1})	Correlation
[3]	0.10	—	0.007–0.0452	2500	—	0.25–4.15	$h = 0.029(\rho_m \rho_g U/D_p)^{0.263}$
	0.0254	—	0.0102–0.0285	2500	—	2.47–4.27	
[4]	0.0175		Alumina–silica catalyst		0–270	11.58–23	$hD_t/k_g = 0.14(D_t U \rho_g/\mu)^{0.6}(W/U\rho_g)^{0.45}$ for $(W/\rho_g U) > 1$
[5]	0.0064		0.0004–0.02	1300–2800	76–10890	0.60–18.9	$hD_p/k_g = (c_p\mu/k_g)(\rho_m/\rho_p)^{0.3}(U_t^2/gD_p)^{0.21}$
[6]	0.0381		0.005	1070	59.3–276	0.15–6.77	$hD_t/k_g = 0.0784(DU_t\rho_g/\mu)^{0.66}(W/\rho_g U)^{0.45}$
	0.0476		FCC catalyst				
(a) Wall heat transfer							
[3]	0.075	0.0125	0.004–0.0452	2420–2830	—	0.51–2.53	$h = 0.00834(\rho_m^{0.466}/D_p^{0.699})$
[7]	0.10	0.019	0.0053	880	—	0.3–2.00	——
[9]	0.075	0.0095	0.0037	2800	45.3–136	0.56–2.82	$h = 1.27 \times 10^{-5} c_p \rho_p(\rho_m D_t/\rho_p D_p)^{0.518}$
(b) Heat transfer to probe							

from the bed for a period T_c given by

$$T_c = \frac{D_c}{U_c} \tag{3}$$

where

$$U_c = \frac{W}{\rho_p(1-\varepsilon_c)\delta_c}. \tag{4}$$

During this period heat transfer to the cluster takes place by transient heat conduction [2] and h_c can be written as

$$h_c = \left(\frac{4k_c c_c \rho_c}{\pi T_c}\right)^{0.5}. \tag{5}$$

Similarly for bubbles

$$h_b = \left(\frac{4k_g c_g \rho_g}{\pi T_b}\right)^{0.5} \tag{6}$$

where

$$T_b = \frac{D_c(1-\delta_c)}{U_c \delta_c}. \tag{7}$$

Assuming that bubbles contain no particles, and that clusters are at a porosity of ε_c, δ_c can be related to the average fraction of solids in the bed as

$$\delta_c = \frac{(1-\varepsilon)}{(1-\varepsilon_c)}. \tag{8}$$

The thermal conductivity of a cluster may be estimated by the method proposed by Baskakov as explained by Gelperin and Einstein [11]. Assuming cluster porosity to be 0.5 and neglecting the effect of the convective flow component, the thermal conductivity of the cluster may be expressed approximately as

$$\frac{k_c}{k_g} = \left(\frac{k_p}{k_g}\right)^{0.45}. \tag{9}$$

The specific heat of the cluster may be expressed as

$$c_c = c_p(1-\varepsilon_c) + c_g \varepsilon_c. \tag{10}$$

The density of cluster may be expressed as

$$\rho_c = \rho_p(1-\varepsilon_c). \tag{11}$$

From equations (1)–(11), the heat transfer coefficient may be obtained as

$$h = \left(\frac{4k_c c_c U^{1/3} W^{2/3} \rho_m}{\pi D_b \rho_p^{2/3}(1-\varepsilon_c)^{2/3}}\right)^{0.5}\left(1 + \sqrt{\frac{k_g \rho_g c_g(\varepsilon - \varepsilon_c)}{k_c c_c \rho_m (1-\varepsilon_c)}}\right) \tag{12}$$

where

$$\rho_m = \rho_p(1-\varepsilon). \tag{13}$$

The bed density in circulating fluidized beds is still not well understood. Hence, if available, the actual bed density may be used to estimate heat transfer coefficients. Avidan [12] and Kehoe and Davidson [13] observed that equations for bed density developed for cocurrent gas–solid flow of fluidized solids by Matsen [14] explain the observed bed densities approximately for turbulent beds when slug velocity corresponding to double the pipesize was used. Thus,

$$\rho_m = \rho_p(1-\varepsilon_{mf}) \Big/ \left\{1 + \frac{U - U_{mf} - [W\varepsilon_{mf}/\rho_p(1-\varepsilon_{mf})]}{U_{br} + [W/\rho_p(1-\varepsilon_{mf})]}\right\} \tag{14}$$

where

$$U_{br} = 0.35(2gD_t)^{0.5}. \tag{15}$$

This equation may be used to estimate bed density in the absence of any better information.

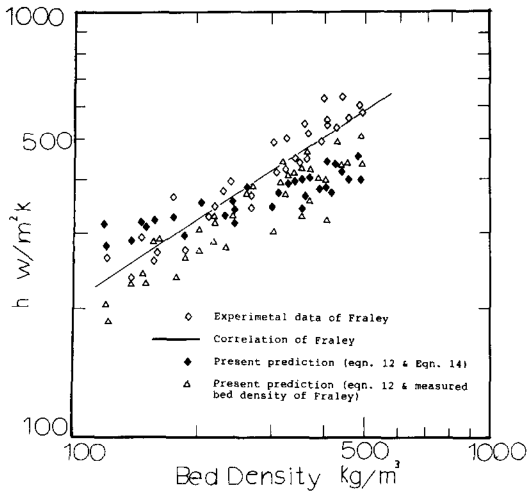

FIG. 1. Dependence of heat transfer coefficient on bed density.

DISCUSSION

The various equations derived together with equation (12) provide an expression for the heat transfer coefficient. It can be seen that the heat transfer coefficient is mainly a function of gas and solid flow rates as well as bed density.

Only data of Fraley *et al.* [9] can be used to test the validity of this equation as only they reported gas and solid flow rates as well as bed densities. Fraley *et al.* [9] studied heat transfer from a probe of 0.95 cm OD to a flowing gas–solid mixture through a 7.5-cm-diam. pipe. Depending on Stewart's criteria for slugging, the bed can be considered to be slugging and hence D_b is taken as equal to the hydraulic mean diameter of the annular clearance between probe and pipe wall. Cluster porosity is taken as 0.5. Using the measured densities, estimated heat transfer coefficients are shown as a function of bed density on the graph of Fraley *et al.* [9] in Fig. 1. It can be seen that the predictions are very close to the experimental observations. Heat transfer coefficients predicted by using bed densities estimated from the equation of Matsen [14] are also shown in Fig. 1. The trend is reasonably good.

Most of the experimental data are obtained in smaller diameter pipes and the beds were slugging. The contribution of heat transfer to bubbles is very small compared to heat transfer to clusters. Neglecting heat transfer to bubbles, equation (12) can be written as

$$\frac{hD_t}{k_g} = \left(\frac{6.35k_p^{0.45}c_c\mu}{\pi k_g^{1.45}}\right)^{0.5}\left(\frac{\rho_m}{\rho_p^{2/3}\rho_g^{1/3}}\right)^{0.5} \times\left(\frac{D_t U\rho_g}{\mu}\right)^{0.5}\left(\frac{W}{\rho_g U}\right)^{0.33}. \quad (16)$$

This equation resembles the correlation of Danziger [6] though it predicts a further effect of bed density—that heat transfer coefficients are independent of particle size and decrease with increase in column diameter. Experimental work is in progress to evaluate this model in further detail.

CONCLUSION

Equation (16) along with equation (14) may be used to estimate surface heat transfer coefficients in circulating fluidized beds.

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