Journal of Engineering Science and Technology
Vol. 3, No. 2 (2008) 131 - 137

A CLUSTER MODEL FOR MASS TRANSFER IN RISERS

DUVVURI SUBBARAO

Department of Chemical Engineering, Universiti Teknologi PETRONAS
Bandar Seri Iskandar, Tronoh, 31750, Perak, Malaysia
Email: Duvvuri_Subbarao@petronas.com.my.

Abstract

Gas to particle mass transfer coefficient in risers was observed to increase with gas velocity, decrease with solid circulation rate and decrease with particle size. A model to explain gas to particle mass transfer in risers is developed considering that particles move as clusters. The model equations compare well with the available experimental observations on gas to particle mass transfer coefficients in risers.

Keywords: Fluid Catalytic Cracker, Riser, Gas to Particle Mass Transfer, Cluster.

1. Introduction

Riser reactors are widely used for catalytic cracking, combustion of coal, calcinations of lime, etc. The reactions are fast and mass transfer limitation can play an important role on the reactor performance. Information on gas to particle mass transfer in high velocity fluidized beds is very limited. Breault [1] presented a review of the available literature on gas to particle mass transfer in circulating fluidized beds. Shen and Kwauk [2] used adsorption of halogen tracer on active carbon particles to estimate mass transfer coefficients in a fast fluidized bed which was dense at the bottom and lean at the top. Van der Ham et al [3] reported experimental observations on mass transfer of naphthalene to FCC catalyst particles (D_p=70 μm, ρ_p = 880 kg/m^3) in a high velocity packed bed riser of 6 cm by 6 cm square cross section (stacked 1 cm diameter rods at a pitch of 2 cm perpendicular to flow.)

Vollert and Werther [4] studied adsorption of NO on Hopkalit catalyst and estimated gas to particle mass transfer coefficients. Experimental observations of Gambhir [5] on mass transfer of naphthalene from gas to sand particles (D_p = 196

Nomenclatures

c_1	Constant
D_{cl}	Cluster diameter, m
D_m	Diffusion coefficient, m^2/s
D_p	Particle diameter, m
D_t	Column diameter, m
D_v	Void diameter, m
k_{cl}	Mass transfer coefficient based on cluster size, m/s
k_p	Mass transfer coefficient based on particle size, m/s
m	Constant
N	Mass transfer flux, kg moles/m^2/s
Nu	Nusselt Number
n	Constant
Re_p	Particle Reynolds number
Sh_{rp}	Sherwood number for particles in riser, k_pD_p/D
Sh_{sp}	Sherwood number for single particles
s_{cl}	Cluster surface area, m^2
s_p	Particle surface area, m^2
u_o	Superficial gas velocity, m/s
u_t	Terminal velocity of particle, m/s
V_b	Volume of bed, m^3
v_{cl}	Volume of cluster, m^3
v_p	Volume of a particle, m^3
W	Solid feed flux, kg/m^2.s
Greek Symbols	
Δc	Concentration difference, kg moles/m^3
δ_{cl}	Cluster fraction
ε_{cl}	Cluster voidage fraction
$(1-\varepsilon)$	Average bed particle fraction
μ	Viscosity of gas, kg/m.s
ρ	Density of gas, kg/m^3
ρ_p	Particle density, kg/m^3

and 390 μm and ρ_p of 2630 kg/m^3) in a 2.5 cm diameter riser at 4, 5 and 6 m/s gas velocity with solid circulation rates up to 60 kg/m^2.s are shown in Fig. 1.

It was observed that the mass transfer coefficient

- increases with gas velocity for the same solid circulation flux,
- decreases with increase in solid circulation flux, and
- decreases with increase in particle diameter.

Generally, data on gas to particle mass transfer coefficients in fluidized beds are presented in terms of Sherwood number as a function of Reynolds number along with the expected Froesling correlation for mass transfer to a single particle [7]. Observations of Gambhir and Subbarao [6] and van der Ham et al [3] on mass transfer coefficients in terms of Sherwood as a function of Reynolds numbers are presented in Fig. 2.

It can be seen that the Sherwood numbers for fast fluidized bed are well below the single particle line. Also, Sherwood numbers observed in the work of Gambhir

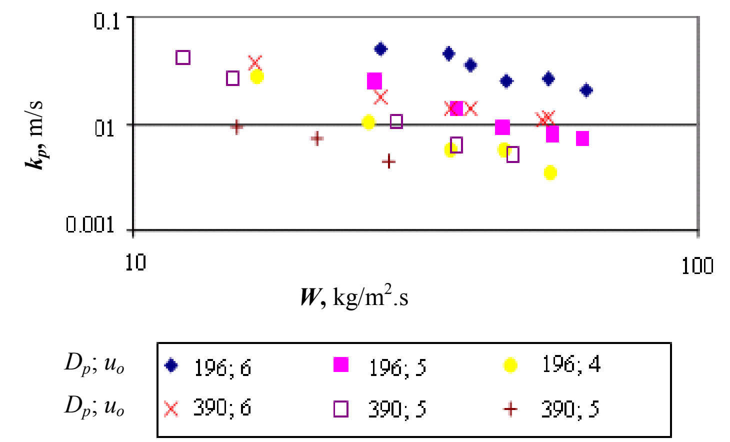

Fig. 1. Experimental Observations of Gambhir [5] on Mass Transfer Coefficients.

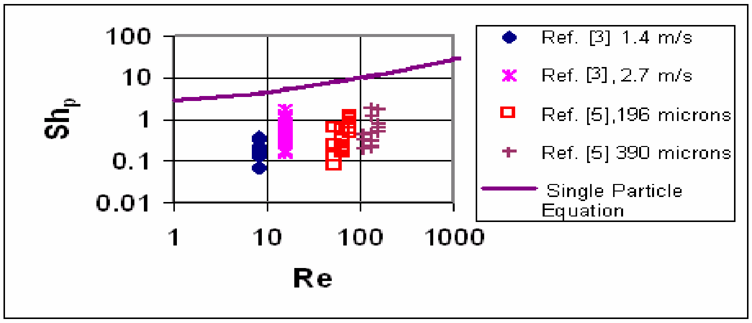

Fig. 2. Comparison of Experimentally Measured Sherwood Numbers as Function of Reynolds Number with the Correlation for Mass Transfer to a Single Particle.

and Subbarao [6] are in the same range as those observed by van der Ham et al [3]. It should be noted that in such a graph, the effect of solid circulation flux is missed. For a given gas velocity (and Reynolds number), as mass transfer coefficients decrease with increase in solid circulation flux, Sherwood numbers also decrease with increasing solid circulation flux.

Present note describes a model for gas to particle mass transfer in risers considering that particles move as clusters.

2. Model for Mass Transfer Coefficients in Risers

Inefficient gas solid contacting may be the manifestation of aggregative nature of gas particle flows. It is well recognized that particles in high velocity fluidized bed regimes move in the form of clusters and they can be impervious to flow of gas through them [8-10]. Then, mass transfer coefficients to such clusters can be estimated by using the available correlations with particle size replaced by cluster size.

$$\frac{k_{cl}\ D_{cl}}{D_m} = c_1 \left(\frac{D_{cl}\ u_o\ \rho}{\mu} \right)^n \tag{1}$$

Based on gas to cluster mass transfer, gas to cluster mass transfer coefficient, k_{cl}, based on cluster surface area can be defined as

$$\begin{aligned} & N = k_{cl} \frac{V_b \delta_{cl}}{v_{cl}} s_{cl} \Delta c \qquad \text{with} \\ & \delta_{cl} = (1-\varepsilon_{cl}) = 1-\varepsilon \\ & v_{cl} = \frac{\pi D_{cl}^3}{6} \qquad \text{and} \\ & \delta_{cl} = \pi D_{cl}^2 \end{aligned} \tag{2}$$

However, experimentally measured mass transfer coefficient are based on particle surface area

$$N = k_p \frac{V_b (1-\varepsilon)}{v_p} s_p \Delta c \tag{3}$$

From Eqs. (1) and (3)

$$k_p \frac{(1-\varepsilon)}{D_p} = k_{cl} \frac{1}{D_{cl}} \frac{(1-\varepsilon)}{(1-\varepsilon_{cl})} \tag{4}$$

This can be rearranged as

$$\begin{aligned} \frac{k_{cl}\ D_{cl}}{D_m} &= \frac{k_p\ D_p}{D_m} \left(\frac{D_{cl}}{D_p} \right)^2 (1-\varepsilon_{cl}) = c_1 \left(\frac{D_{cl}\ u_o\ \rho}{\mu} \right)^n \\ &= c_1 \left(\frac{D_p\ u_o\ \rho}{\mu} \right)^n \left(\frac{D_{cl}}{D_p} \right)^n \end{aligned} \tag{5}$$

From this, Sherwood number in risers based on particle size can be written as

$$Sh_{rp} = \frac{k_p\ D_p}{D_m} = c_1 \left(\frac{D_p\ u_o\ \rho}{\mu} \right)^n \left(\frac{D_{cl}}{D_p} \right)^{n-2} \frac{1}{1-\varepsilon_{cl}} \tag{6}$$

Sherwood number for mass transfer to a single particle can be written as

$$Sh_{sp} = \frac{k_{sp}\ D_p}{D_m} = c_1 \left(\frac{D_p\ u_o\ \rho}{\mu} \right)^n \tag{7}$$

Taking ratio of both Sherwood numbers

$$\frac{Sh_{rp}}{Sh_{sp}} = \left(\frac{D_{cl}}{D_p}\right)^{n-2} \frac{1}{1-\varepsilon_{cl}} \tag{8}$$

Subbarao [9] proposed that, in non choked beds, ratio of cluster volume to void volume will be in proportion to the ratio of their volumetric flow rates and obtained an equation for the cluster size as

$$D_{cl} = \left(\frac{W}{\rho_p\, u_o\, (1-\varepsilon_{cl})}\right)^{1/m} D_v \tag{9}$$

with "*m*" equal to 3. Subbarao [9] proposed that diameter of void can be taken as

$$\begin{aligned} D_v &= \frac{2\, u_t^2}{g} && \textit{for} \quad D_v < D_t/4 \\ &= D_t && \textit{for} \quad D_v \geq D_t/4 \end{aligned} \tag{10}$$

These equations can be combined to obtain

$$\frac{Sh_{rp}}{Sh_{sp}} = \left(\frac{W}{\rho_p u_o}\right)^{(n-2)/m} \frac{1}{(1-\varepsilon_{cl})^{((n-2)/m)+1}} \left(\frac{D_v}{D_p}\right)^{n-2} \tag{11}$$

The exponent "*n*" is expected to be between 0 and 0.5; parameters "*m*" and "ε_{cl}" are assigned values of 3 and 0.5 respectively.

3. Results and Discussion

Ratio of experimental particle Sherwood numbers in risers to single particle Sherwood Numbers are presented as a function of $u_o\rho_p/W$ on a log-log plot as shown in Fig. 3.

The correlation by regression analysis of the data is obtained as

$$\frac{Sh_{rp}}{Sh_{sp}} = 7\times 10^{-4}\left(\frac{u_o\, \rho_p}{W}\right)^{0.693} \qquad \text{for } 200 < u_o\, \rho_p\, /W < 6500 \tag{12}$$

DATA OF VAN DER HAM ET AL [3]:

FCC particles of 70 micron size with terminal velocity of 13 cm/s were used by van der Ham et al [3]. Void size D_v is estimated as 0.347 and appears to be smaller than the hydraulic diameter of the packing employed. Assuming *n* to be

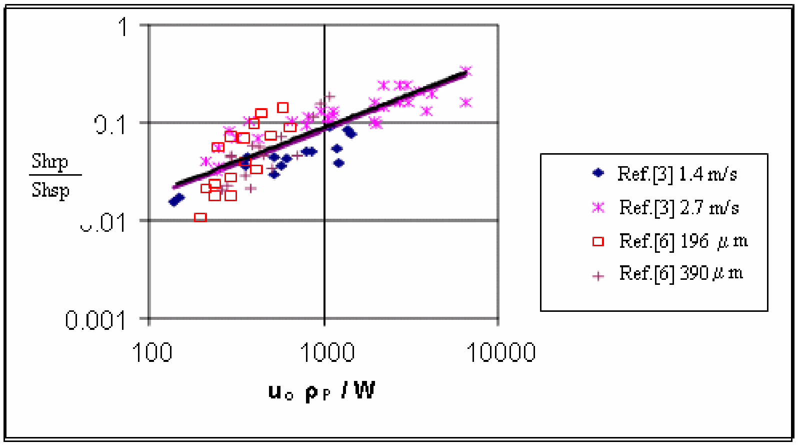

Fig. 3. Correlation of Mass Transfer Sherwood Numbers as a Function of Ratio of Gas to Particle Velocities.

zero, Eq. (11) for the data of van der Ham et al [3] reduces to

$$\frac{Sh_{rp}}{Sh_{sp}} = 5.12\times10^{-4}\left(\frac{u_o\,\rho_p}{W}\right)^{0.67} \tag{13}$$

This result compares very well with Eq. (12).

DATA OF GAMBHIR [5]

Gambhir [5] used sand particles of two sizes (196 and 390 microns). As terminal velocities of these particles are high, the void size is limited by column diameter (2.5 cm) and can be approximately taken as equal to a quarter of the column diameter. Assuming n to be zero, Eq. (12) for the data of Subbarao and Gambhir [6] for 196 micron size particles (D_v= 0.6225 cm) reduces to

$$\frac{Sh_{rp}}{Sh_{sp}} = 1.2\times10^{-3}\left(\frac{u_o\,\rho_p}{W}\right)^{0.67} \tag{14}$$

and for 390 micron size (D_v=0.632 cm) reduces to

$$\frac{Sh_{rp}}{Sh_{sp}} = 4.75\times10^{-3}\left(\frac{u_o\,\rho_p}{W}\right)^{0.67} \tag{15}$$

These estimates are slightly higher than the observations. The model expects an effect of particle size and column diameter for coarse particles. These need to be further investigated.

4. Conclusions

- Gas to particle mass transfer coefficient decreases with increase in solid circulation flux for all the gas velocities and particle sizes. Mass transfer coefficient increases with increase in superficial gas velocity for the same solid circulation flux.
- A model for gas to particle mass transfer is developed assuming particles move as impermeable clusters. The model equation is used to correlate data as

$$\frac{Sh_{rp}}{Sh_{sp}} = 7 \times 10^{-4} \left(\frac{u_o \, \rho_p}{W} \right)^{0.693} \qquad \text{For } 200 < u_o \rho_p / W < 6500$$

- Effect of column diameter for coarse particles needs to be further investigated.

Acknowledgement

The author acknowledges the support of Universiti Teknologi PETRONAS in the preparation of this paper.

References

1. Breault, R. W. (2007). A Review of Gas–Solid Dispersion and Mass Transfer Coefficient Correlations in Circulating Fluidized Beds. *Powder Technology*, 163, 9-17.
2. Shen, Z. and Kwauk, M. (1985). Mass Transfer between Gas and Solids in Fast Fluidization. *Circulating Fluidized Bed Technology*, P. Basu, (Ed).
3. Van der Ham, A. G. V., Prins, W. and van Swaaij, W. P. M. (1991). Hydrodynamics and Mass Transfer in Regularly Packed Circulating Fluidized Bed. *Circulating Fluidized Bed Technology III*, P. Basu, M. Horio, M. Hasatani, Eds., 605-612 .
4. Vollert, J. and Werther, J. (1994). Mass Transfer and Reaction Behaviour of a Circulating Fluidized Bed Reactor. *Chem. Eng. Technol*. 17, 201-209.
5. Gambhir, S. (1999). Studies in Circulating Beds. Ph.D Thesis, IIT Delhi.
6. Subbarao, D. and Gambhir, S. (2002). Gas to Particle Mass Transfer in Risers. *Circulating Fluidized Bed Technology VII*, Ed. J. R. Grace, J. Zhu, H. de Lasa, 97-104.
7. Kunii, D. and Levenspiel, O. (1969). *Fluidization Engineering*. John Wiley & Sons, New York, 1969.
8. Matsen, J. M. (1982). Mechanism of Choking and Entrainment. *Powder Technology*, 32, 21-33.
9. Subbarao, D. (1986). Clusters and Lean Phase Behaviour. *Powder Technology*, 36, 101-107.
10. Horio, M. and Kuroki, H. (1994). Three Dimensional Flow Visualization of Dilutely Dispersed Solids in Bubbling and Circulating Fluidized Beds. *Chem. Eng. Sci*, 49, 2413-2421.