A MODEL FOR GAS TO PARTICLE MASS TRANSFER IN RISERS

D.Subbarao
Department of Chemical Engineering
Indian Institute of Technology, Delhi
New Delhi, 110 016, India

ABSTRACT

A model for gas to particle mass transfer is developed considering that particles move as clusters. Available experimental observations on gas to particle mass transfer in risers are explained in the light of model equations. Gas to particle mass transfer coefficients increase with gas velocity, decrease with solid circulation rate and decrease with particle size.

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. Information on gas to particle mass transfer in high velocity fluidized beds is very limited. Shen and Kwauk [1985] used adsorption of halogen tracer with active carbon particles to estimate mass transfer coefficients in a fast fluidized bed which is dense at the bottom and lean at the top.van der Ham et al [1991] reported experimental observations on mass transfer of naphthalene to FCC catalyst particles (D_p=70 μm, $_p$ = 880 kg/m^3) in a high velocity packed bed riser of 6 cm by 6 cm square cross section bed (stacked with 1 cm diameter rods at a pitch of 2 cm perpendicular to flow). Vollert and Werther [1994] studied adsorption of NO on Hopkalit catalyst and estimated gas to particle mass transfer coefficients. Gambhir [1999] and Subbarao and Gambhir [2002] reported experimental observations on mass transfer from gas to sand particles (D_p = 190 and 360 μm and $_p$ 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 upto 60 kg/m^2.s. It is 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.

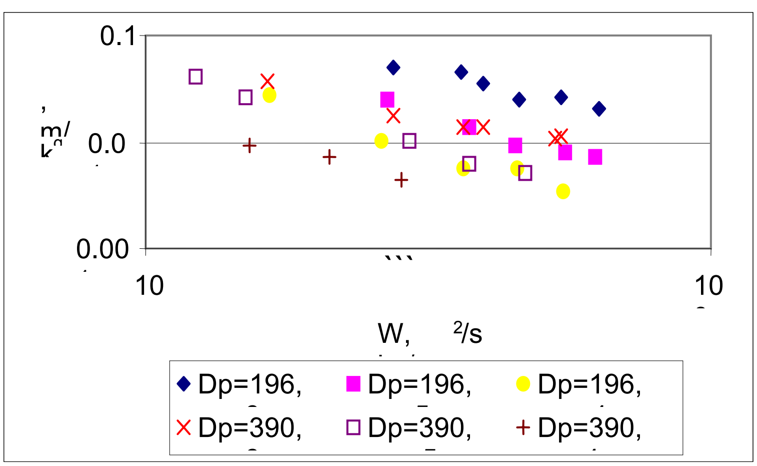

Fig.1 Experimental observations of Gambhir [1999] on Mass Transfer Coefficients

Figure 1 shows the experimental observations of Gambhir [1999] on mass transfer coefficients as a function of solid circulation flux for three superficial air velocities (4,5 and 6 m/s) and for the two particle sizes (196 and 390 microns).

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 (Kunii and Levenspiel [1991]).

$$Sh_{sp} = 2 + 0.6\,\mathrm{Re}_p^{\,0.5}\,Sc^{0.33} \qquad (11)$$

Present observations on mass transfer coefficients along with the observations of van der Ham et al [1991] in terms of Sherwood and Reynolds Numbers are presented in Figure 2.

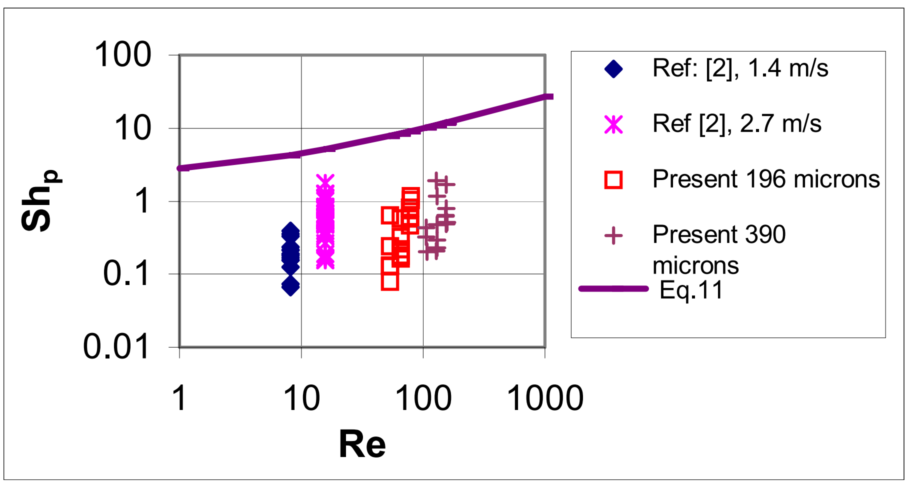

Fig.2 Comparison of experimentally measured Sherwood Numbers as function of Reynolds number with the correlation for mass transfer to a single particle

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 present work are in the same range as those observed by van der Ham et al [1991] though the Reynolds Numbers are different. 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 gas to particle mass transfer considering that particles move as clusters.

2 Model for Mass Transfer Coefficients

Inefficient gas solid contacting may be the manifestation of aggregative nature leading to particles moving as clusters. It is well recognized that, in high velocity fluidized bed regimes, particles move in the form of clusters (Matsen [1982], Subbarao [1986], Horio and Kuroki [1994]). Larger clusters lead to poorer gas-solid contact as particles with in the cluster are not exposed to gas as much as the particles on the surface of clusters. In view of this, mass transfer coefficient is to be defined based on cluster surface area as

$$N = k_{cl} \frac{V_{bed}\, \delta_{cl}}{v_{cl}} s_{cl}\, \Delta c$$

$$with \qquad (1)$$

$$\delta_{cl} = \frac{1-\varepsilon}{1-\varepsilon_c}$$

Such cluster based mass transfer coefficients can be correlated as Sherwood Number as a function of Reynolds Number based on cluster size as

$$\frac{k_{cl}\, D_{cl}}{D_m} = c_1 \left(\frac{D_{cl}\, u_{og}\, \rho}{\mu} \right)^n \qquad (2)$$

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

$$N = k_p \frac{V_{bed}\, (1-\varepsilon)}{v_p} s_p\, \Delta c \qquad (3)$$

From eqns. 1 and 3

$$k_p \frac{1}{D_p} = k_{cl} \frac{1}{D_{cl}} \frac{1}{(1-\varepsilon_c)} \qquad (4)$$

This can be rearranged as

$$\frac{k_{cl}\, D_{cl}}{D_m} = \frac{k_p\, D_p}{D_m} \left(\frac{D_{cl}}{D_p} \right)^2 (1-\varepsilon_c) = c_1 \left(\frac{D_{cl}\, u_{og}\, \rho}{\mu} \right)^n = c_1 \left(\frac{D_p\, u_{og}\, \rho}{\mu} \right)^n \left(\frac{D_{cl}}{D_p} \right)^n \qquad (5)$$

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

$$Sh_{rp} = \frac{k_p\, D_p}{D_m} = c_1 \left(\frac{D_p\, u_{og}\, \rho}{\mu} \right)^n \left(\frac{D_{cl}}{D_p} \right)^{n-2} \frac{1}{1-\varepsilon_c} \qquad (6)$$

For mass transfer to a single particle, this reduces to

$$Sh_{sp} = \frac{k_{sp}\, D_p}{D_m} = c_1 \left(\frac{D_p\, u_{og}\, \rho}{\mu} \right)^n \qquad (7)$$

Taking a ratio of the two

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

Subbarao [1986] 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

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

with "m" equal to 3. Subbarao [1986] proposed that diameter of void can be taken as

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

These two cases can be combined to obtain

$$D_v = \frac{1}{\dfrac{g}{2\,u_t^{\,2}} + \dfrac{4}{D_t}} \tag{11}$$

These equations can be combined to obtain

$$\frac{Sh_{rp}}{Sh_{sp}} = \left(\frac{W}{\rho_p u_{og}}\right)^{(n-2)/m} \frac{1}{(1-\varepsilon_c)^{((n-2)/m)+1}} \left(\frac{D_v}{D_p}\right)^{n-2} \tag{12}$$

Results and Discussion

The exponent "n" is expected to be between 0 to 0.5. In view of this, the observed data are correlated with $u_{o\ p}/W$ as shown in Figure 3.

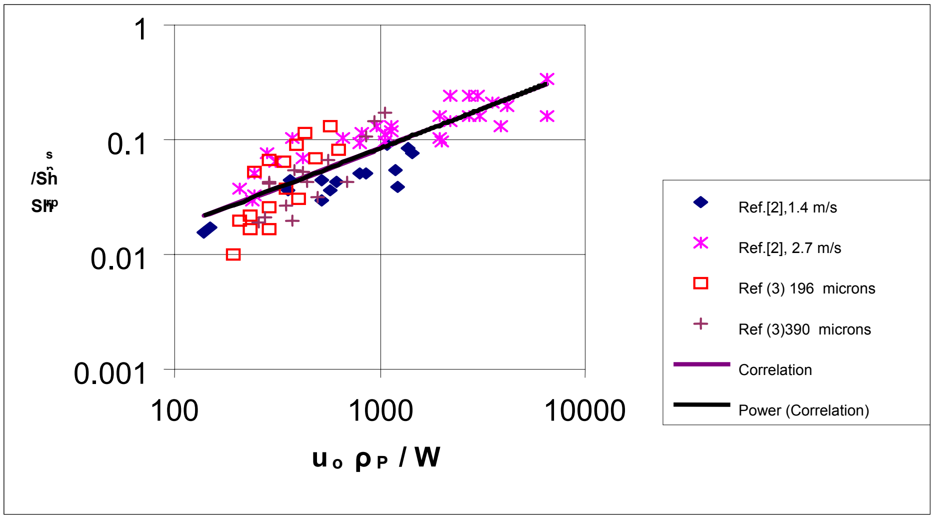

Fig 3 Correlation of Mass transfer Sherwood Numbers as a function of ratio of gas to particle velocities

The correlation is reasonably good. The following equation is obtained by regression analysis of the data

$$\frac{Sh_{rp}}{Sh_{sp}} = 7.10^{-4}\left(\frac{u_o\,\rho_p}{W}\right)^{0.693} \qquad \text{for } 200 < u_o\ _p/W < 6500 \qquad (13)$$

Data of van der Ham et al [1991] :

FCC particles of 70 micron size with terminal velocity of 13 cm/s were used by van der Ham et al [1991]. 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 zero, eq.12 for the data of van der Ham et al [1991] reduces to

$$\frac{Sh_{rp}}{Sh_{sp}} = 5.12.10^{-4}\left(\frac{u_o\,\rho_p}{W}\right)^{0.67} \qquad (14)$$

This model equation compares well with the experimental observations.

Data of Gambhir [1999]_

Gambhir [1999] used sand particles of two sizes (196 and 390 microns). As terminal velocities of theses particles are high, the void size is limited by column diameter 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 [2002]

for 196 micron size particles (D_v= 0.6225 cm) reduces to

$$\frac{Sh_{rp}}{Sh_{sp}} = 1.2.10^{-3}\left(\frac{u_o\,\rho_p}{W}\right)^{0.67} \qquad (15)$$

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

$$\frac{Sh_{rp}}{Sh_{sp}} = 4.75.10^{-3}\left(\frac{u_o\ \rho_p}{W}\right)^{0.67} \tag{16}$$

These estimates are higher than the observations. Also, the model expects an effect of particle size which is not supported by the limited amount of experimental observations. The model also suggests a strong effect of column diameter for coarse particles. These need to be further investigated.

Heat Transfer

Watanabe et al [1991] investigated gas to particle heat transfer in high velocity fluidized beds in a 180 cm long 2.1 cm diameter column. Three sizes of glass beads (194, 305 and 506 microns with density of 2.5 gm/cm^3) and activated alumina of 648 micron size (density 0.65 gm/cm^3) were used in their experiments. They observed that gas to particle heat transfer Nusselt Numbers decreased with particle holdup. They also observed distinct effect of particle size and the data can be approximately correlated as

$$Nu \quad = \quad 1.223\,\frac{D_p}{D_t}\,(1-\varepsilon)^{-1.2} \tag{17}$$

Assuming homogeneous flow (for argument sake)

$$\frac{W}{u\ \rho_p} \quad \propto \quad \frac{1-\varepsilon}{\varepsilon} \quad \propto \quad 1-\varepsilon \tag{18}$$

With this,

$$Nu \quad \propto \quad 1.223\frac{D_p}{D_t}\left(\frac{u\ \rho_p}{W}\right)^{1.2} \tag{19}$$

This equation is very similar to equation (12). The higher value of exponent indicates possibility of “m” to be around 1 instead of 3 suggested by Subbarao [1986] for coarser particles. Value of “n” appears to be 1 at least for coarse particles. It is to be noted that data of Subbarao and Gambhir [2002] correlate as

$$Sh_{rp} \quad = \quad 8.314\,.\,10^{-5}\left(\frac{u_o\rho_p}{W}\right)^{1.43}$$

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 is gas to particle mass transfer is developed assuming particles move as impermeable clusters. The data are correlated as

$$\frac{Sh_{rp}}{Sh_{sp}} = 7\,.\,10^{-4}\left(\frac{u_o\ \rho_p}{W}\right)^{0.693}$$

for 200 < u_o $_p$ /W < 6500

Further is work is needed to confirm the effect of particle size and column diameter.

NOMENCLATURE

D_m	Diffusion coefficient, m^2/s
D_{cl}	Diameter of Cluster, m
D_p	Diameter of particle, m
D_t	Column Diameter, m
D_v	Diameter of the void, m
k_{cl}	Mass transfer coefficient based on cluster size, m/s
k_g	Mass transfer coefficient based on particle size, m/s
N	Mass Transfer flux, kg moles/m^2/s
Nu	Nusselt Number, [-]
Re_p	Particle Reynolds Number, [-]
s_p	Surface area of a particle, m^2
s_{cl}	Surface area of a cluster, m^2
Sh_{rp}	Sherwood Number for particles in riser, $k_g D_p$/D[-]
Sh_{sp}	Sherwood Number for single particles, [-]
u_o	Superficial gas velocity, m/s
V_b	Volume of bed, m^3
V_p	Volume of a particle, m^3
v_{cl}	Volume of cluster, m^3
W	Solid feed flux, kg/m^2/s

Greek Letters

•c	Concentration difference, kg moles/m^3
$_{cl}$	Cluster fraction
$_c$	Cluster voidage
(1-)	Average bed particle fraction
μ	Viscosity of gas, kg/m/s
	Density of gas, kg/m^3
$_p$	Particle density, kg/m^3

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