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Short communication

Solid–liquid mass transfer in a gas–liquid–solid three-phase reversed flow jet loop reactor

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Abstract

Solid–liquid mass transfer in gas–liquid–solid three-phase reversed flow jet loop reactors was experimentally investigated by means of an electrochemical method, and the effects of liquid jet flow rate, gas jet flow rate, particle size, particle density and nozzle diameter on the solid–liquid mass transfer coefficient were evaluated. The solid–liquid mass transfer coefficients in gas–liquid–solid three-phase reversed flow jet loop reactors are higher than those in the corresponding liquid–solid two-phase reversed flow jet loop reactors. A generalized correlation is developed which more accurately and conveniently predicts solid–liquid mass transfer in gas–liquid–solid three-phase reversed flow jet loop reactors.

Keywords: Solid–liquid mass transfer; Gas–liquid–solid three-phase flow; Reversed jet loop reactors

1. Introduction

Gas–liquid–solid three-phase jet loop reactors, characterized by a well defined flow pattern, better dispersing effects, relatively lower power consumption, and a higher mass transfer coefficient, are widely used in chemical engineering and petrochemical engineering. They are also used in biochemical processes, such as fermentation and waste water purification. Hydrogenation and exhaust-gas treatment and a large number of gas–liquid–solid three-phase reactions are encountered in various process industries [1,2]. In gas–liquid–solid three-phase reversed flow jet loop reactors, solid–liquid mass transfer may play an important role in the performance of these reactors, and the accurate prediction and understanding of factors controlling the solid–liquid mass transfer are a necessary part of any design or evaluation strategy.

In recent years a number of studies have appeared in the literature investigating solid–liquid mass transfer in gas–liquid–solid three-phase fluidized beds and bubble column reactors [3–7]. Little is known, however, about solid–liquid mass transfer in gas–liquid–solid three-phase reversed flow jet loop reactors. The objective of the present study is to thoroughly examine the influences of liquid jet flow rate, gas jet flow rate, particle size, particle density and nozzle diameter on solid–liquid mass transfer in gas–liquid–solid three-phase reversed flow jet loop reactor, and to develop the solid–liquid mass transfer coefficient correlation which is convenient, accurate and generally applicable to gas–liquid–solid three-phase reversed flow jet loop reactors.

2. Experimental

A gas–liquid–solid three-phase reversed flow jet loop reactor with a central draft tube and a gas–liquid two-fluid nozzle at the top was used in the present investigation. An important advantage of this reactor is that it is operated in two zones: one internal downstream gas–liquid zone with high gas–liquid transfer and a three-phase(annular) zone with recirculation of liquid phase in the riser. The experimental setup is shown in Fig. 1. A 550 mm high Perspex draft tube of 60 mm in diameter was fixed concentrically inside the main 820 mm high Perspex reactor tube of 102 mm in diameter. Four concentric gas–liquid two-fluid nozzles of 4.8, 5.4, 6.2 and 6.8 mm were located 75 mm above

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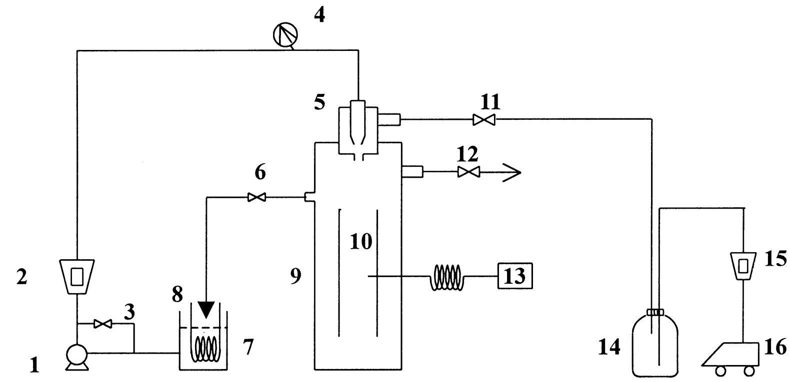

Fig. 1. Schematic drawing of experimental apparatus: (1) water pump; (2,15) rotameter; (3) by-pass control valve; (4) pressure gauge; (5) nozzle; (6,11 and 12) drain valve; (7) tank; (8) heat exchanger; (9) reactor; (10) draft tube; (13) measuring system of particle electrode; (14) air buffer and (16) air compressor.

the draft tube. Two outlets are provided at the top sides (680 mm from the bottom) of the reactor. A circular baffle of 102 mm in diameter was fixed 10 mm below these outlets to prevent the direct outflow of the solid particles with the liquid. All the experiments were performed at atmospheric pressure and the temperature of the liquid was maintained around 25±0.1°C by circulating the tap water through a copper coil heat exchanger immersed in a water tank. This would correspond to an error of less than ±1% on the limiting current for the ferro–ferricyanide system according to Berger [8], thus measurement precision could be assured. The liquid was made from equal volumes of 2×10^{-3} M potassium ferricyanide solution, and 0.2 N sodium hydroxide solution mixed together. The physicochemical properties of the liquid were: $\mu=1.05\times10^{-3}$ Pa s, $\rho=1006$ kg/m^3, $D=6.97\times10^{-10}$ m^2/s, Sc=1500. Nitrogen was used as the gas phase. The sizes and densities of the solid particles of equal diameter are summarized in Table 1, and the volume of solids added was 0.20×10^{-3} m^3 corresponding to a solids volume fraction 3.1%.

The method used, similar to that used by Hassanien [9], involved a fixed spherical electrode immersed in a fluidized bed of inert particles of the same diameter as the fixed sphere. Prakash [10] demonstrated that in three-phase fluidized beds, free-floating and tethered particles had nearly the same solid–liquid mass transfer coefficient. Del Pozo [11] then demonstrated that fixed and tethered particles had nearly the same solid–liquid mass transfer coefficient. These indicate that a fixed electrode could be used to measure solid–liquid mass transfer coefficients in gas–liquid–solid three-phase fluidized bed reactors. Solid–liquid mass transfer coefficients in this reactor were measured by the well-known electrochemical method, using the diffusion controlled cathode reduction of ferricyanide ions. The cathode(the measuring probe), fixed at the axial position of 0.18 m below the nozzle, was a 5 mm gold-plated brass sphere, and four different diameters were successively used, 3, 6,8 and 10×10^{-3} m, equal to the fluidized particles. The anode was the cylindrical part of the column wall, near the exit of liquid, a saturated calomel electrode was employed as the reference electrode. The overall solid–liquid mass transfer coefficient k_S is related to the limiting current intensity by

$$k_S = \frac{I}{n_e F A_S C_b} \tag{1}$$

giving for the Sherwood number

$$\mathrm{Sh} = \frac{k_S d_S}{D} = \frac{I d_S}{n_e F A_S C_b D} \tag{2}$$

Table 1
Properties of the fluidized particles

Material	$d_s\times10^{-3}$ (m)	$\rho_s\times10^{-3}$ (kg/m^3)
Plastic sphere	3	1.34
	6	1.34
	8	1.34
	10	1.34
Glass sphere	3	2.52
	6	2.52
	8	2.52
	10	2.52

3. Experimental results and discussion

3.1. Behavior of the overall solid–liquid mass transfer coefficients of the gas–liquid–solid three-phase reversed flow jet loop reactor

3.1.1. Effect of gas jet flow rate on k_S

Qualitatively, in gas–liquid–solid three-phase reversed jet loop reactors, the liquid–solid mass transfer, which is directly related to the turbulence intensity of liquid according to the Levich three-zone model [12], varies with the turbulence intensity in the liquid phase which is generated by gas agitation. But the turbulence affects the solid–liquid mass

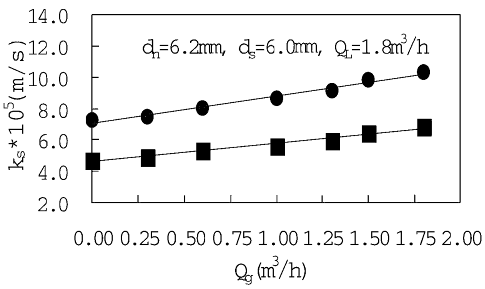

Fig. 2. Relationship of solid–liquid mass transfer coefficient to gas jet flow rate: (●) glass sphere; (■) plastic sphere.

transfer in two different conflicting ways. On the one hand, turbulence intensity may increase the effective liquid–solid contact area, increasing solid–liquid mass transfer coefficient, and on the other hand, turbulence can also increase the drag coefficient, therefore, decrease the particle terminal velocity, which decreases solid–liquid mass transfer coefficient. However, with the increase in gas jet flow rate, solid–liquid mass transfer coefficient of gas–liquid–solid three-phase reversed flow jet loop reactor increases as shown in Fig. 2, which is in accordance with the findings of gas–liquid–solid three-phase fluidized beds [3–7].

3.1.2. *Effect of liquid jet flow rate on k_S*

Fig. 3 presents the effect of liquid jet flow rate on solid–liquid mass transfer coefficient in gas–liquid–solid three-phase reversed flow jet loop reactor. In agreement with the results of solid–liquid mass transfer of gas–liquid–solid three-phase fluidized beds [3–7], no effect of liquid jet flow rate on solid–liquid mass transfer coefficient was observed.

3.1.3. *Effect of the particle diameter on k_S*

Fig. 4 shows the relation between k_S and the particle size. It is found that the solid–liquid mass transfer coefficient is quite independent of the solid particle diameters. This result has been observed to be of general validity.

3.1.4. *Effect of the nozzle diameter on k_S*

The solid–liquid mass transfer coefficient slightly decreases with increase of the nozzle diameter as seen in Fig. 5. This may be due to the fact that at the same liquid

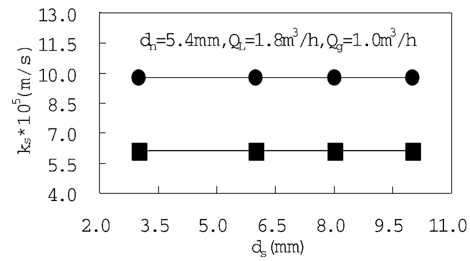

Fig. 4. Relationship of solid–liquid mass transfer coefficient to the particles diameter: (●) glass sphere; (■) plastic sphere.

and gas jet flow rates, an increase in the nozzle diameter raises the bubble diameter and decreases the number of bubbles around the measuring probe, resulting in a decrease in solid–liquid mass transfer coefficient [6].

3.1.5. *Effect of the particle density on k_S*

From Figs. 2-5, it can also be observed that the overall solid–liquid mass transfer coefficient increases with increase in the solid particle density.

3.2. *Comparison of solid–liquid mass transfer coefficients in liquid–solid two-phase and gas–liquid–solid three-phase reversed flow jet loop reactors*

When gas is introduced into the liquid–solid two-phase reversed flow jet loop reactors, turbulence in the liquid phase is intensified by the bulk liquid flow and gas agitation. Hence, solid–liquid mass transfer coefficients of gas–liquid–solid three-phase reversed flow jet loop reactors are higher than those of liquid–solid two-phase reversed jet loop reactors, as shown in Fig. 6.

3.3. *Correlation of k_S*

It is desirable to establish a general equation which accurately and conveniently predicts solid–liquid mass transfer of reversed flow jet loop reactors, both liquid–solid two-phase and gas–liquid–solid three-phase, over the entire range of data available. The approach chosen utilizes an existing solid–liquid mass transfer correlation of liquid–solid two-phase reversed flow jet loop reactors to which a suit-

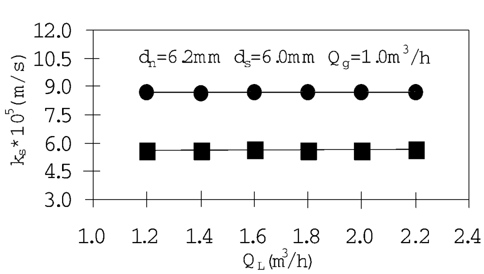

Fig. 3. Relationship of solid–liquid mass transfer coefficient to liquid jet flow rate: (●) glass sphere; (■) plastic sphere.

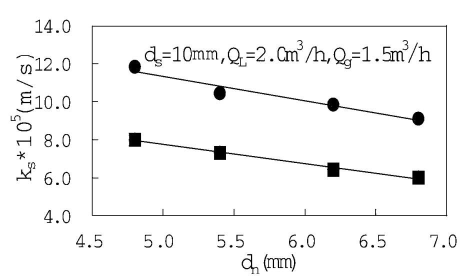

Fig. 5. Relationship of solid–liquid mass transfer coefficient to the nozzle diameter: (●) glass sphere; (■) plastic sphere.

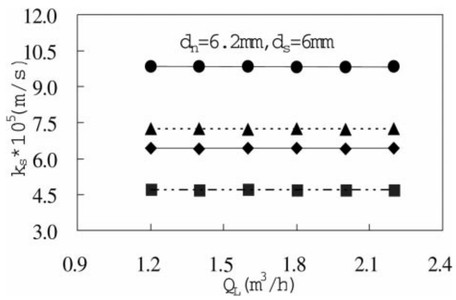

Fig. 6. Comparison of solid–liquid mass transfer coefficients in liquid–solid two-phase and gas–liquid–solid three-phase reversed flow jet loop reactors: (●) experimental data of gas–liquid–glass particles three-phase flow at Q_g=1.5 m^3/h; (▲) experimental data of liquid–glass particles two-phase flow at Q_g=0 m^3/h; (◆) experimental data of gas–liquid-plastic particles three-phase flow at Q_g=1.5 m^3/h and (■) experimental data of liquid-plastic particles two-phase flow at Q_g=0 m^3/h.

able gas effect term is added. In the case of the Sherwood number, for example:

$$\mathrm{Sh} = (1.0 + \alpha Q^{\beta})\mathrm{Sh}_2 \quad (3)$$

where Sh_2 represents the values obtained from the solid–liquid mass transfer correlation of liquid–solid two-phase reversed flow jet loop reactors and Q is the as yet unspecified gas effect term. In order to fit two-phase as well as three-phase data, Q must equal zero where the gas rate equals zero. Once a suitable gas term and base two-phase correlation are chosen, the coefficients α and β can be determined using a simple least-squares fit.

In liquid–solid two-phase reversed flow jet loop reactors, the best fit of solid–liquid mass transfer is the Sherwood number equation of Wen et al. [13]

$$\mathrm{Sh}_2 = 1.4920\,\mathrm{Re}_n^{0.054}\,\mathrm{Ga}^{0.323}\,\mathrm{Mr}^{0.300}\,\mathrm{Sc}^{0.400} \quad (4)$$

with average and maximum deviations of 2.4% and less than 15%, respectively.

Eq. (3) presents a versatile equation form with which to predict solid–liquid mass transfer of both two- and three-phase reversed flow jet loop reactors. Eq. (4) provides a suitable base correlation of liquid–solid two-phase reactors. A gas term must also be chosen which includes the effects discussed experimentally, i.e. a positive dependence on gas rate, independence of liquid rate and particle size, and a dependence on the nozzle diameter. A superficial gas-jet Reynolds number, defined as:

$$\mathrm{Re}_g = \frac{d_n U_g \rho_g}{\mu_g} = \frac{4 Q_g \rho_g}{\pi \mu_g d_n} \quad (5)$$

contains the requisite parameters in a likely arrangement.

Substituting the gas-jet Reynolds number for Q in Eq. (3) and fitting the experimental data with a least-squares method results in

$$\mathrm{Sh} = 1.4920(1.0 + 0.0003\,\mathrm{Re}_g^{0.7795})\,\mathrm{Re}_n^{0.054}\,\mathrm{Ga}^{0.323}\,\mathrm{Mr}^{0.300}\,\mathrm{Sc}^{0.400} \quad (6)$$

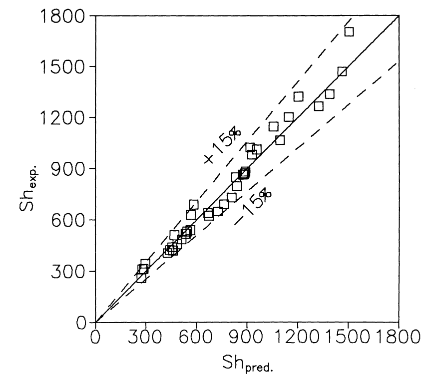

Fig. 7. Comparison of the experimental data with the prediction.

Fig. 7 presents the experimental values of the Sherwood number of solid–liquid mass transfer data versus the values predicted by Eq. (6). Most of the data is seen to lie within ±15% of the prediction.

4. Conclusions

1. Solid–liquid mass transfer coefficients in gas–liquid–solid three-phase reversed flow jet loop reactors are found to increase with increasing particle density and gas jet flow rate, and to be independent of liquid jet flow rate. They are also independent of particle size, but slightly dependent on nozzle diameter.
2. The solid–liquid mass transfer coefficient is correlated well by Eq. (6). The agreement between the experimental data and the prediction is quite good.

5. Nomenclature

A	transfer area (m^2)
C_b	concentration of electroactive species (kmol/m^3)
D	molecular diffusivity of electroactive species (m^2/s)
d_n	nozzle diameter (m)
d_S	particles diameter (m)
F	Faraday number
Ga	Galileo number$=d_S^3\rho_L g/\mu_L^2$
g	gravitational acceleration (m/s^2)
I	diffusion limiting current (A)
k_S	solid–liquid mass transfer coefficient (m/s)
Mr	density number$=(\rho_S-\rho_L)/\rho_L$
n_e	number of electrons involved in the electrochemical reaction
Q_L	liquid jet flow rate (m^3/s)
Q_g	gas jet flow rate (m^3/s)
Q	mass transfer gas effect term in Eq. (3)
Re_n	liquid-nozzle Reynolds number$=U_L d_n \rho_L/\mu_L$
Re_g	gas-nozzle Reynolds number$=d_n U_g \rho_g/\mu_g$
Sc	Schmidt number$=\mu_L/D\rho_L$

Sh Sherwood number $=k_S d_S/D$
U average superficial fluid velocity (m/s)

Greek letters
α constants of Eq. (3)
β constants of Eq. (3)
μ fluid viscosity (Pa s)
ρ density (kg/m^3)

Subscripts
g gas phase
l liquid phase
s solid phase
2 specific to the two-phase liquid–solid system

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