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Gas–Liquid Mass Transfer in Continuous Oscillatory Flow in a Baffled Column

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Gas–liquid mass transfer in continuous oscillatory flow was conducted in a vertical baffled column. Pure carbon dioxide (CO_2) was used as the dispersed phase and tap water was used as the continuous phase. The mass transfer rate of CO_2 measured under continuous operation was expressed in terms of the liquid-side volumetric mass transfer coefficient (k_La) and was calculated using a stationary method. The effects of oscillation frequency, oscillation amplitude, and flow rates on mass transfer were also determined. The results showed that a significant increase in mass transfer could be achieved in oscillatory flow in a baffled column compared to that in a bubble column. The mass transfer in continuous oscillatory flow in a baffled column was not affected by the liquid flow rate in the range tested. Then, k_La was correlated as a function of power density and superficial gas velocity.

Keywords: Baffle columns, fluid oscillation, liquid-side volumetric mass transfer coefficient (k_La), mass transfer improvement, power consumption, *and* superficial gas–liquid velocity.

INTRODUCTION

Contact between gas phase and liquid phase plays a key role in many chemical processes, especially when mass transfer between the phases is the rate-controlling step for the overall process. Mass transfer can take place from the gas phase to the liquid phase and vice versa. Often, but not necessarily, the mass transfer is accompanied by the simultaneous occurence of chemical reaction. A good understanding of gas–liquid mass transfer behavior is essential for the design of gas–liquid contactors. Gas–liquid contactors exist in a number of configurations. One of these contactors is the *oscillatory baffled column,* which has been reported in numerous publications as a very promising way to improve mixing in columns (Mackley 1987, 1991; Hewgill et al. 1993). Its radial velocity component is comparable to the axial velocity component, giving enhanced mixing in both directions (Brunold et al. 1989, Dickens et al. 1989). As a result, heat and mass transfer are significantly improved (Mackey 1990, Hewgill et al. 1993).

The fluid mechanics within a baffled column is controlled by geometrical configuration of the baffles and two dimensionless parameters. The first parameter is the *oscillatory Reynolds number,* Re_o, which describes the intensity of mixing applied to the column.

$$Re_o = \frac{\omega \rho x_o D}{\mu} \tag{1}$$

The second parameter is the *Strouhal number*, *St*, which represents a ratio of column diameter to stroke length, measuring effective eddy propagation (Ni and Gough 1997).

$$St = \frac{D}{4 \pi x_o} \tag{2}$$

If there is an additional net flow along the tube, a net flow Reynolds number (Re_n) becomes relevant,

$$Re_n = \frac{\rho U_l D}{\mu} \tag{3}$$

Brunold et al. (1989) showed that the baffle spacing in order 1.5 column diameter and the constriction ratio of about 60% were optimal to achieve good mixing in oscillatory condition. Mackay et al. (1991) indicated that the wall baffle (orifice-type) gave the impression of a more chaotic flow compared to a central baffle. This means that overall mixing appears to be greater for orifice baffles than for central baffles.

Research on gas–liquid mass transfer enhancement via oscillatory flow in baffled columns, however, has received little attention in recent years (Hewgill et al. 1993, Ni et al. 1995). Research has so far been concentrated on the semibatch system with the liquid phase in the batch mode and the mass transfer rates calculated using the dynamic method.

Thus, this work aims to investigate liquid–mass transfer in continuous oscillatory flow in a baffled column. The liquid-side volumetric mass transfer coefficient ($k_L a$) was determined based on a stationary method. The mass transfers were correlated as a function of power density and superficial gas velocity.

MATERIALS AND METHODS

A schematic diagram of the experimental apparatus is shown in Figure 1. The experiments were conducted in a vertical Perspex column with a height of 1,200 mm and a diameter of 94 mm with the top open to the atmosphere. Seven orifice-type baffle plates with a spacing of 141 mm in between plates supported by two stainless steel rods with a 6-mm diameter were installed in the column. The diameter of the baffle is 94 mm and each baffle has a central hole with a 50-mm diameter. A pneumatically driven piston mounted at the bottom of the column was used to oscillate the liquid phase. Oscillation frequency can be varied by adjusting the air pressure from the compressor to the pneumatic unit to provide frequencies in the range of 0.5–2.0 Hz. Various oscillation amplitudes can be obtained by adjusting the distance between two sensors at the pneumatic cylinder to give amplitudes in the range of 10–40 mm. The range of experimental conditions are summarized in Table 1.

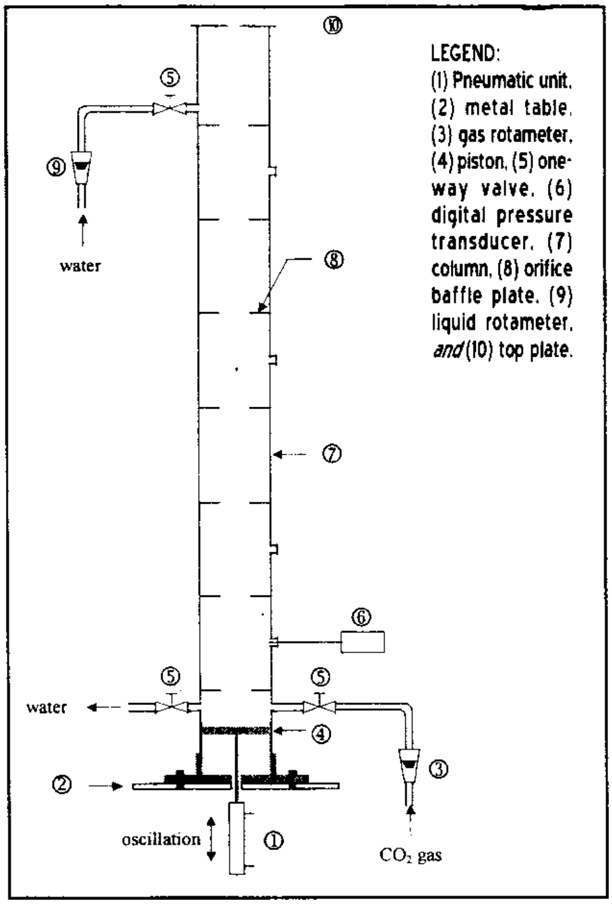

Figure 1. Experimental Apparatus

Pure carbon dioxide (CO_2) was used as the dispersed phase while tap water was used as the continuous phase in which both phases flowed continuously. Tap water at room temperature (27–29°C) was pumped into the column at a certain rate while the dispersed phase was fed countercurrently via a 3-mm diameter nozzle.

Table 1. Experimental Conditions

Condition	Specifications/Range
Oscillation frequency, f	0.5–2.0 Hz
Oscillation amplitude, x_o	10–40 mm
Superficial gas velocity, U_g	0.026–0.072 m/s
Inside column diameter, D	94 mm
Column height, H	1,200 mm
Orifice diameter, D_o	50 mm
Baffle spacing	141 mm
Number of baffles, N	7
Thickness of each baffle	3 mm
Diameter of supporting rods	6 mm

The concentration of dissolved CO_2 in the continuous phase were measured by titration. Assuming complete mixing of the liquid phase (Kojima et al. 1987), the mass transfer coefficient was obtained using the following equation:

$$k_L a = \frac{(C_2 - C_1)}{(C_i - C_2)} \frac{Q_L}{V} \tag{4}$$

with C_i as the concentration of CO_2 at gas–liquid interphase, which was estimated from the Henry's law (Butler 1982),

$$[CO_2] = K_H P_{CO2} \tag{5}$$

where K_H is the Henry's constant; and P_{CO2}, the static pressure of CO_2 at fixed location in the column, which was measured using a digital pressure transducer.

The mass transfer coefficient was correlated in terms of *power density* (P/V), or power consumed per unit volume, and *superficial gas velocity*. Estimation of the power density was closely related to both oscillation frequency and amplitude and was derived on the work of Jealous and Johnson (1955).

This method calculates pressure drop across an orifice plate, and assumed that there is no net flow of fluid in the main column or on the pulse line. This should be a fairly sound assumption because the superficial velocities of liquid flow in an oscillatory baffled column are generally smaller relative to the velocities of the fluid bulk generated by pulsing. Integrating the work done over a complete cycle and allowing for a number of orifice plates give a time-averaged power density (Baird and Stonestreet 1995):

$$(P/V)_{OBC} = \frac{2\rho N}{3\pi C_D^2}\left(\frac{1-\alpha^2}{\alpha^2}\right) x_o^3 \, \omega^3 \tag{7}$$

RESULTS AND DISCUSSION

Mass transfer

Mass transfer experiments in the absence of baffles and oscillation were first carried out to establish a basis for comparison with mass transfer studied under oscillatory conditions. Each run was conducted for Re_n in the range of 130–520. Figure 2 shows the results of the volumetric mass transfer coefficient collected in this study at various conditions. The figure shows that mass transfer is better in the presence of baffles compared to a straight smooth tube in the absence of oscillation. The flow direction was altered due to the presence of baffles and, to some extent, improve on the degree of mixing. Thus, a higher degree of mass transfer was observed in the presence of baffles.

The effect of liquid oscillation on mass transfer capability was also investigated. The experiments with liquid oscillation were conducted at a constant value of oscillatory Reynolds number or the oscillation parameters, namely (a) the amplitude and (b) the frequency, were kept constant. The $k_L a$ was plotted against the net Reynolds number as show in Figure 2. The figure shows that fluid oscillation alone has very little effect on mass transfer capability. When both liquid oscillation and baffles were present in the tube, vigorous vortices occured in the space between two baffles and, consequently, uniform mixing was achieved. As a result, greater gas–liquid mass transfer was obtained.

The value $k_L a$ in continuous flow in a baffled column (f = 1 Hz and x_0 = 4 cm) was approximately three times greater than that of steady flow in a bubble column (no baffles, no oscillation). The results also showed that the mass transfer coefficients were not affected by liquid flow rate in the range used in this study. The present results are consistent with the results obtained by Kojima et al. (1987) in a continuous-stirred vessel.

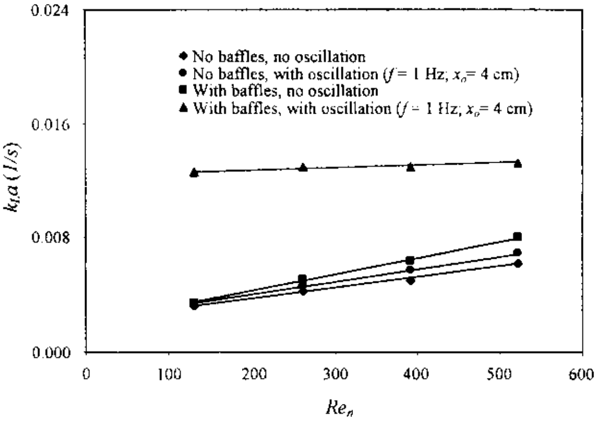

Figure 2. Mass Transfer Coefficients Obtained for Various Conditions at U_g = 0.048 m/s

Several experimental runs were performed to determine the effect of oscillation amplitude at various fixed oscillation frequencies. The k_La was plotted against the Strouhal number in Figure 3.

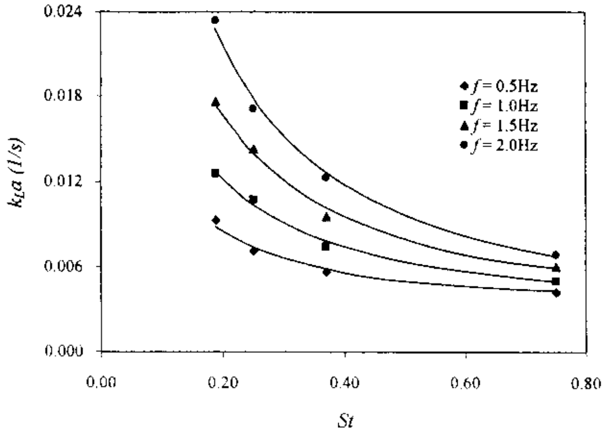

Figure 3. Mass Transfer Coefficients at Various Strouhal Numbers and Oscillation Frequencies, U_g = 0.048 m/s and Re_n = 130

The graph shows that for a given frequency, the k_La decreases with increasing St, and that for a given St, the k_La is greater for higher frequencies. As the liquid oscillated back and forth, a certain amount of the fluid backmixed into the previous baffled cell. At a constant frequency, a longer amplitude (or lower St) displaced the liquid farther while the liquid at the baffled cell were pushed farther into the adjacent baffled cell resulting in a greater level of backmixing. As a result, lower k_La was observed. At a constant St, vigorous vortices are generated from the interaction of the liquid and the edge of the baffles for higher values of oscillation frequency, giving a higher k_La.

Additional experimental runs were carried out to investigate the effect of gas superficial velocity on mass transfer. Experiments with different oscillation frequencies and fixed amplitude were conducted at various fixed gas flow rates. The liquid flow rate was kept constant at an Re_n of 130. The k_La was plotted against the oscillatory Reynolds number in Figure 4. It can be seen that for a given Re_o, the mass transfer increases with superficial gas velocity, and for a given gas velocity, the mass transfer also increases with Re_o.

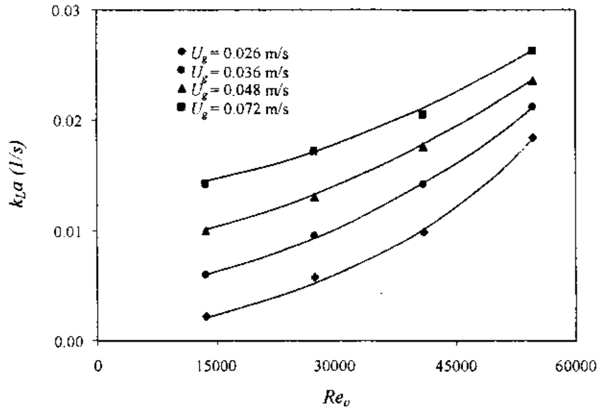

Figure 4. Mass Transfer Coefficient at Various Oscillatory Reynolds Numbers and Superficial Gas Velocities, Re_n = 130

Generally, the increase in gas flow rate caused an increase in the number of bubbles. Under an oscillatory condition, smaller bubbles were formed due to the interaction of fluid oscillation and the baffles' edges. Smaller bubbles have lower rising velocity, thus remain longer in the column. Besides the formation of more bubbles, gas flow is subjected to a higher drag through plate holes. As a result, significant increase in mass transfer were observed. At lower gas velocities, the effect of oscillation frequency is more significant than at higher gas velocities as shown in Figure 4. Therefore, increasing the oscillation frequency at certain gas velocity would increase the intensity of mixing in the column. Thus, the mass transfer is also significantly improved.

The k_La under oscillatory condition and power density from Eq. (7) were plotted together in Figure 5 at fixed superficial gas velocity. This figure shows that mass transfer increases significantly at a lower range of power density of up to 500 W/m³. Beyond this value, the mass transfer increases in a linear fashion. At higher values of power density, mixing becomes more intense, giving a higher degree of mass transfer. However, the degree of increase in mass transfer was found to be less for higher power densities than for lower densities. This might suggest that a threshold in the uniformity of mixing in oscillatory flow through a baffled column exists. Once the column has reached such a uniformity, further increase in power density would not impact on mass transfer.

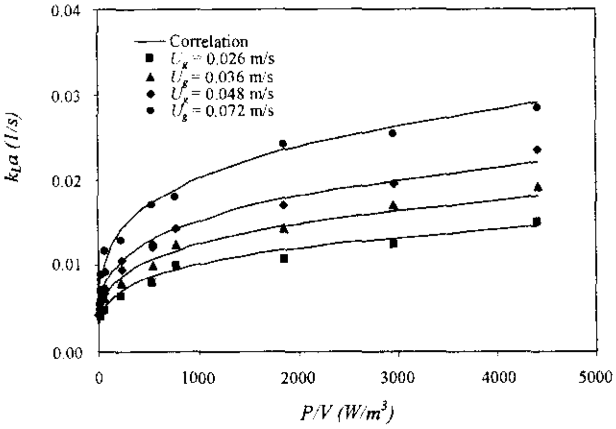

Figure 5. The k_La vs. Power Density Calculated Using Eq. (6) at Various Gas Velocities, Re_n = 130

CORRELATION

Kojima et al. (1987) derived a general correlation between k_La and power density for a gas-sparger system in a continuous-agitated vessel:

$$k_La = a\,(P/V)_{ST}^{b}\,U_g^{c} \tag{8}$$

The present data were fitted with power density calculated using Eq. (6) and U_g to general form as shown in Eq. (7) to give:

$$k_La = 0.022(P/V)_{OBC}^{0.25}\,U_g^{0.69} \tag{9}$$

Figure 6 shows the experimental data plotted against the values of k_La and calculated using the correlation of Eq. (8). Each data point in Figure 6 represents one experiment. These data show good agreement with the correlation. As of press time, this correlation is the only one that has been developed for oscillatory flow in a baffled column under a continuous operation condition.

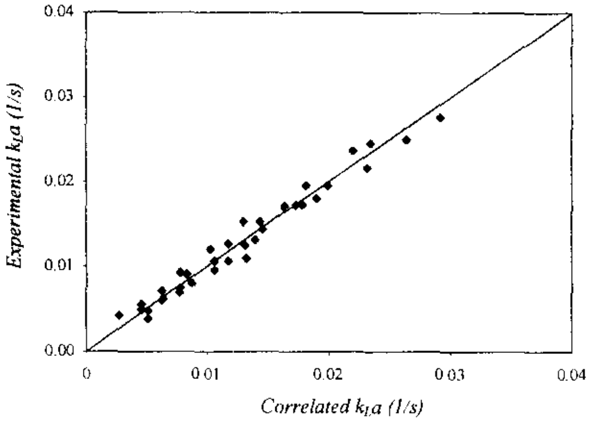

Figure 6. Experimental k_La Data vs. Calculated Data Using Correlation of Eq. (8)

CONCLUSIONS

The experimental results showed that mass transfer in continuous operation significantly improved in a gas–liquid oscillatory flow in a baffled column compared to that in a bubble column.

The presence of liquid oscillation alone or baffles alone in the column showed little effect on mass transfer. When orifice baffles were inserted into the column, mass transfer improvement became a strong function of both the amplitude and the frequency of oscillation.

Moreover, mass transfer also increased with superficial gas velocity. However, liquid flow rate did not appear to have any effect on the mass transfer in oscillatory flow through a baffled column in the range tested. A correlation of mass transfer to power density and superficial gas velocity was been developed for continuous oscillatory flow in a baffled column.

NOTATIONS

a	Constant
b	Constant
c	Constant
C_D	Orifice discharge

	coefficient (usually taken as 0.7)	
C_1	Concentration of dissolved CO_2 at inlet stream	$kmol/m^3$
C_2	Concentration of dissolved CO_2 at outlet stream	$kmol/m^3$
C_i	Concentration of CO_2 at gas–liquid interface	$kmol/m^3$
D	Column inside diameter	m
f	Oscillation frequency	Hz
K_H	Henry's constant	
k_La	Liquid-side volumetric mass transfer coefficient	$1/s$
N	Number of baffles per unit length	$1/m$
OBC	Oscillatory baffled column	
P/V	Power density	W/m^3
Q_L	Volumetric liquid flow rate	m^3/s
Re_n	Net flow Reynolds number	
Re_o	Oscillatory Reynolds number	
St	Strouhal number	
ST	Sitrred tank/vessel	
U_g	Superficial gas velocity	m/s
U_l	Superficial liquid velocity	m/s
V	Volume of column	m^3
x_o	Center to peak amplitude of oscillation	m
a	Ratio of orifice area to tube area	
r	Liquid density	kg/m^3
m	Liquid viscosity	$kg/m.s$
w	Angular frequency of oscillation $(2\pi f)$	rad/s

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