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Gas Holdup and Gas-Liquid Mass Transfer Investigations in an Oscillatory Baffled Column

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Gas holdup and gas-liquid mass transfer were investigated 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. Gas holdup and mass transfer rate of CO_2 were measured under semi-batch condition, while the liquid phase was measured in batch mode. Gas holdup was estimated as the volume fraction of the gas in the two-phase mixture in the column. Mass transfer was expressed in terms of the liquid-side volumetric mass transfer coefficient (k_La). The effects of oscillation frequency, oscillation amplitude and gas flow rate on gas holdup and mass transfer were also determined. The results showed that a significant increase in gas holdup and mass transfer could be achieved in an oscillatory baffled column compared to a bubble column. Gas holdup and mass transfer were correlated as a function of power density and superficial gas velocity.

Keywords: gas holdup, mass transfer coefficient, power density, superficial gas 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. Gas holdup and mass transfer coefficients are important parameters in the charaterization and design of gas-liquid contactors, and oscillatory baffled columns are no exceptions. Oscillatory baffled columns have been reported in numerous publications as a promising method to improve mixing in columns (Mackley, 1987 & 1991). The radial velocity component is comparable to the axial velocity component, giving enhance 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 the 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.

$$Re_0 = \frac{\rho \omega x_0 D}{\mu} \tag{1}$$

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

$$St = \frac{D}{4 \pi x_0} \tag{2}$$

Brunold *et al.*, (1989) indicated that the baffle spacing of order 1.5 column diameter and

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the constriction of ratio to about 60% was optimal to achieve good mixing in oscillatory condition. Mackay *et al.*, (1991) indicated that the wall baffle (orifice type) gives 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 central baffles.

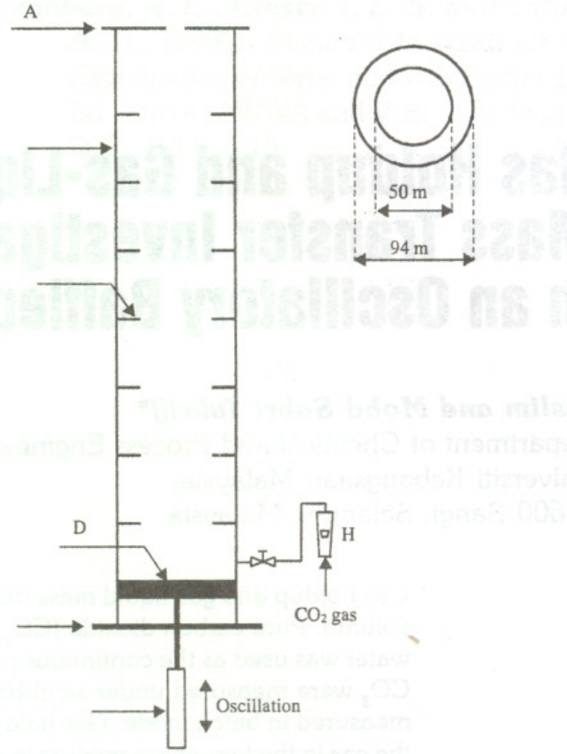
Gas holdup and mass transfer enhancement via oscillatory baffled columns received some attention in recent years (Baird *et. al.*, 1996; Hewgill *et. al.*, 1993). However, these studies were concentrated either on gas holdup or mass transfer only. The objectives of this paper were to investigate gas holdup and gas-liquid mass transfer in an oscillatory baffled column and propose a correlation for gas holdup and mass transfer.

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 1200 mm and a diameter of 94 mm. Its top is 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 of the compressor of the pneumatic unit to provide frequencies ranging from 0.5 to 2.0 Hz. Various oscillation amplitudes can be obtained by adjusting the distance between the two sensors at the pneumatic cylinder to give amplitudes that range from 10 to 40 mm. A summary of the range of experimental conditions used in this work is presented in Tabel 1.

The column was filled with tap water at room temperature and initial liquid height was measured. Compressed CO_2 from a cylinder was fed into the column via a nozzle with a 3 mm diameter and final liquid height was measured. These measurements were made after a steady state was achieved. Volume occupied by the gas phase was estimated from the final liquid volume less the initial liquid volume. The gas holdup (e_g) was determined from the following equation:

$$e_g = V_g/(V_l + V_g) \quad (3)$$



A. Top plate, B. Column, C. Orifice baffle plate, D. Piston
E. Metal table, F. Pneumatic unit, G. One way valve, H. Rotameter

Figure 1. Schematic diagram of experimental apparatus

Table 1. Details of experimental conditions

Details	Range
Oscillation frequency, f	0.5 – 2.0 Hz
Oscillation amplitude, x_0	10 – 40 mm
Superficial gas velocity, U_g	0.026 – 0.072 m/s
Inside column diameter, D	94 mm
Column height, H	1200 mm
Orifice diameter, D_0	50 mm
Baffle spacing	141 mm
Number of baffles, N	7
Thickness of baffles	3 mm
Diameter of supporting rods	6 mm

Rate of CO_2 transfer from the CO_2 bubble to the liquid phase can be described using the following relationship, assuming there is complete mixing of the liquid phase.

$$dC/dt = k_La\,(C^* - C) \quad (4)$$

The concentration of dissolved CO_2 in the continuous phase was measured by titration. Integrating Equation (4) gives:

$$\ln(C^* - C) = -k_La\,t + \text{constant} \quad (5)$$

The k_La can be directly determined by plotting $\ln(C^*-C)$ against t. The k_La is the slope of the straight line obtained.

In the case of a bubble column contactor, mixing is induced pneumatically. The total specific power density (P/V) can be related to the dispersion into the gas liquid mixing according to the following equation (Bouaifi *et. al.*, 2001):

$$(P/V)_{BC} = \rho_l\, g\, U_g \quad (6)$$

In the oscillatory baffled column, estimation of power density was closely related to both oscillation frequency and amplitude and was derived from the work of Jealous and Johnson (1955). This method calculates pressure drop across an orifice plate and integrates the work done over a complete cycle. This gives a time-averaged power density as follows (Baird and Stonestreet, 1995):

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

RESULTS AND DISCUSSION

Gas holdup

Gas holdup experiments in the absence of baffles and liquid oscillation were first carried out to establish a basis for comparison with gas holdup studied under oscillatory condition. The effects of liquid oscillation in the absence of baffles and the presence of baffles without liquid oscillation were also studied. Gas holdup was estimated from raw experimental data using Equation (3). Gas holdup was found to increase with gas velocity. The presence of liquid oscillation and the absence of baffles have negligible effects on gas holdup. On the other hand, the presence of baffles lowers gas holdup. The observation reflected restriction of bubble dispersion, forcing bubbles to flow only through the centre of the column. This results to lower gas holdup.

The dependence of gas holdup on superficial gas velocity for bubble columns can be expressed as:

$$\varepsilon_g = a_1\, U_g^b \quad (8)$$

The experimental data were fitted with superficial gas velocity using Equation (8) to give $a_1 = 1.12$ and $b = 0.9$, which are consistent with the values obtained from the related literature (Shah *et. al.*, 1982). When orifice baffles were inserted into the column without liquid oscillation, the value of a_1 and b became 0.85 and 0.88, respectively.

The dependency of gas holdup versus power density for the bubble column can be written as (Bouaifi *et. al.*, 2001):

$$\varepsilon_g = a_2\, (P/V)_{BC}^c \quad (9)$$

Experimental values of a_2 and c in this study were 0.0003 and 0.89, respectively. If there were baffles in the column, the values of a_2 and c became 0.0002 and 0.87, respectively.

The combined effects of liquid oscillation and the presence of baffles on gas holdup were investigated at difference oscillatory conditions. Gas holdup was plotted against oscillation velocity which is the product of oscillation amplitude and frequency (x_of), as shown in Figure 2. It can be seen that gas holdup increases with gas velocity for a given x_of. Oscillation velocity has minimal effect on gas holdup when x_of is less than 20 mm/s for a given gas velocity. Above this value, oscillation velocity has a big effect on gas holdup. The data trends for this work and a previous work (Baird *et. al.*, 1996) are qualitatively similar.

Gas holdup increased in the presence of liquid oscillation and baffle plates. Generally, increase in gas flow rate causes an increase in the number of bubbles. Under oscillatory

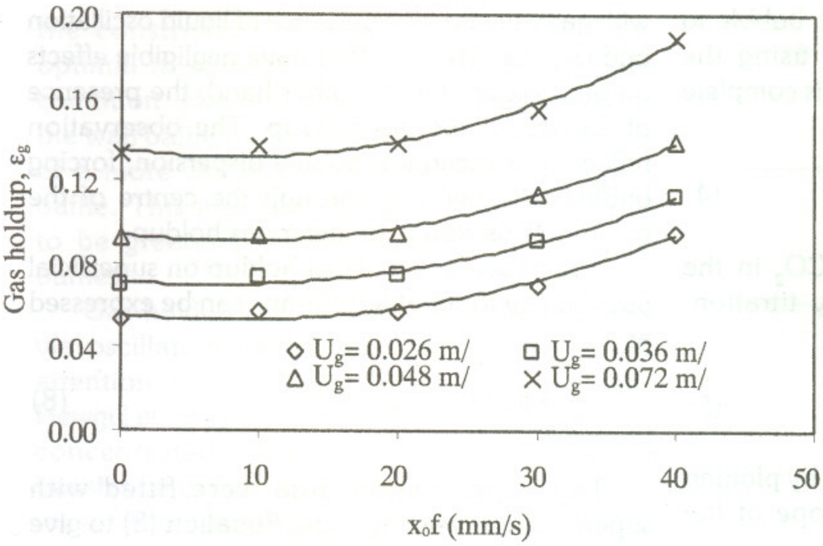


Figure 2. The effect of oscillation velocity (product of oscillation amplitude and frequency) on gas holdup

Fitting the present data with the above correlation yielded a_3 = 0.79, d = 0.1, and e = 0.79. The experimental data and the correlation were plotted together in Figure 3.

condition, small bubbles were formed due to the interaction of fluid oscillation and the baffle edges. Smaller bubbles lowered rising velocity, thus remaining longer in the column. Besides the formation of more smaller bubbles, gas flow is subjected to higher drag through plate holes. As a result, a significant increase in gas hold up is observed.

The gas holdup is plotted against power density calculated using Equation (7) in Figure 3. It can be seen that e_g increases with power density. This figure shows that the gas holdup significantly increases at a lower range of power density reaching up to about 500 W/m³. Beyond this value, gas holdup increases in a linear fashion. Higher power inputs per unit volume led to better mixing intensity and consequently a higher e_g was obtained. In the oscillatory baffled column, correlation of gas holdup as a function of power density and superficial gas velocity can be written as:

$$\varepsilon_g = a_3 (P/V)^d_{OBC} U^e_g \quad (10)$$

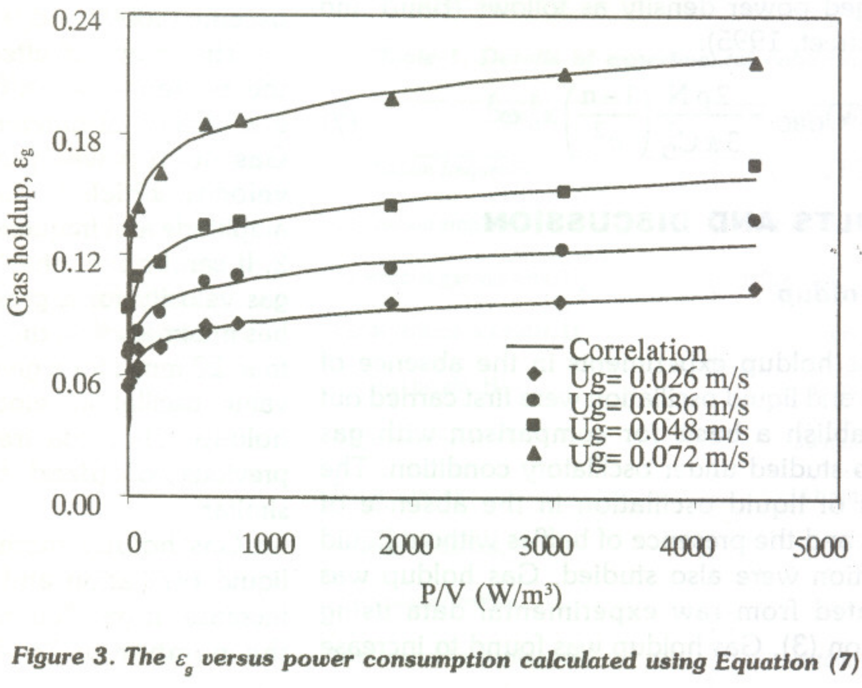


Figure 3. The ε_g versus power consumption calculated using Equation (7)

Mass transfer

The volumetric mass transfer coefficient, k_La, was obtained from experimental data using Equation (5) and the plot for this equation is shown in Figure 4. The values of k_La are the slope of the straight lines in Figure 4 and given in Table 2. The value of k_La in an oscillatory baffled column (f = 1 Hz, x_o = 4 cm) is approximately three times greater than that of a bubble column (NBNO). The k_La in a baffled column was not affected in the presence of liquid oscillation (NBWO) as compared to a bubble column. The presence of baffles without liquid oscillation caused CO_2 to flow only through the centre of column, making gas transfer near the walls more difficult. Under this condition, the k_La obtained was lower compared to that of a bubble column.

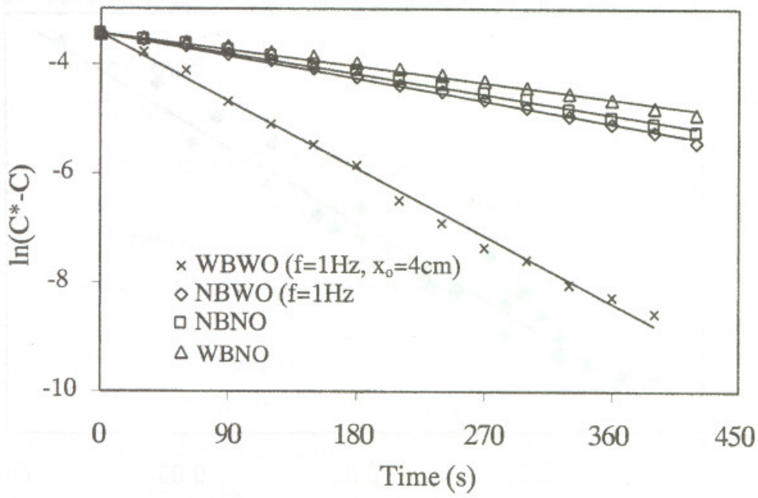


Figure 4. A log plot of the concentration versus time for various conditions at U_g=0.026 m/s

Table 2. The values of k_La for Figure 4

Conditions	k_La, 1/s
With baffles, no oscillation (WBNO)	0.0033
No baffles, no oscillation (NBNO)	0.0044
No baffles, with oscillation (NBWO)	0.0046
With baffles, with oscillation (WBWO)	0.0137

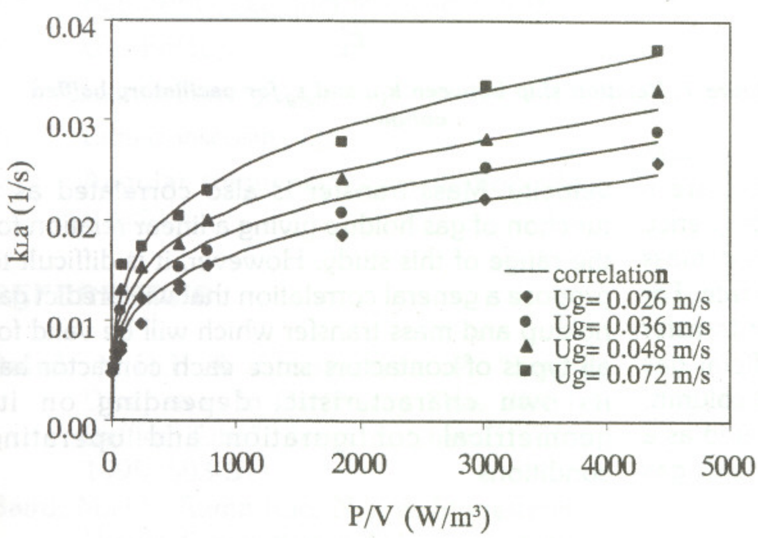


Figure 5. The k_La versus power consumption calculated from Equation (7)

The k_La under oscillatory condition were plotted against power density in Figure 5 at a fixed superficial gas velocity. This figure shows that the k_La increases with power density. At a higher power density, mixing becomes more intense, giving a higher degree of mass transfer. However, the degree of the increase in mass transfer was found to be less for higher power densities than for lower ones. This could suggest that a threshold in the uniformity of mixing in oscillatory baffled columns exists. Once the column reaches such a uniformity, further increase in power density would not have an impact on mass transfer

For the bubble column, the experimental data can be correlated to superficial gas velocity as follows (Deckwer *et. al.*, 1974):

$$k_La = a_4 U_g^f \tag{11}$$

The experimental values give a_4 = 0.079 and f =0.81, which is in close agreement with results found in a related literature (Deckwer *et. al.*, 1974). In the presence of orifice baffles in a column without oscillation, the values of a_4 and f were reduced to 0.059 and 0.79, respectively.

Linek *et.al.*, (1987) derived a correlation between k_La and power density for gas-sparger systems in agitated vessels in general, which was given as follows:

$$k_La = a_5 (P/V)_{ST}^m U_g^n \tag{12}$$

The present data were fitted with power density using Equation (7) to arrive at a general form as shown in Equation (12):

$$k_La = 0.012 (P/V)_{OBC}^{0.26} U_g^{0.4} \tag{13}$$

Figure 6 shows the experimental data plotted versus the values of k_La calculated from the above correlation.

Each data point in Figure 6 represents one experiment. The data show good agreement with the correlation.

Qualitatively, Figures 3 and 5 exhibit a similar trend, suggesting that it may be possible to correlate the k_La as a function of e_g. An effort to correlate the k_La with e_g was made as illustrated in Figure 7. This Figure shows a plot of the k_La against e_g for data obtained in the oscillatory baffled column. The values of the k_La were found to be linearly proportional to gas holdup. Data in Figure 7 were fitted with a straight line with a slope of 0.17.

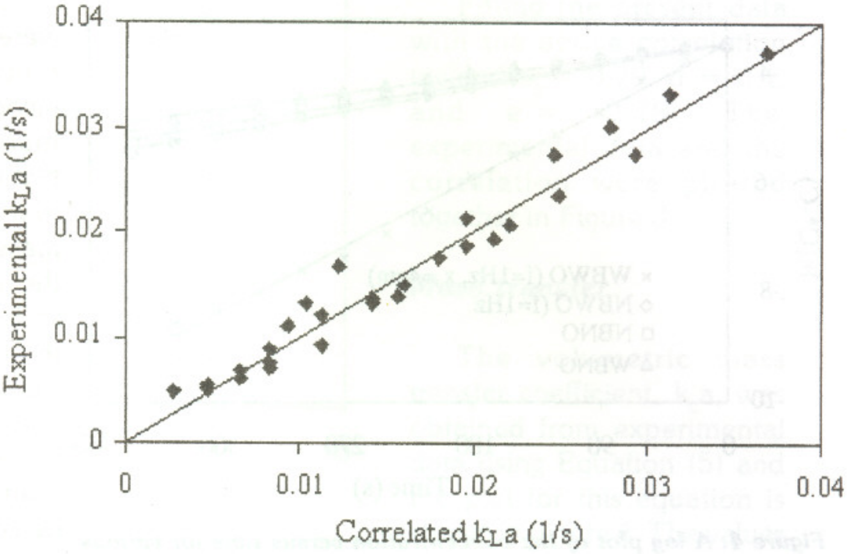


Figure 6. Experimental k_La data versus calculated data using correlation of Equation (13)

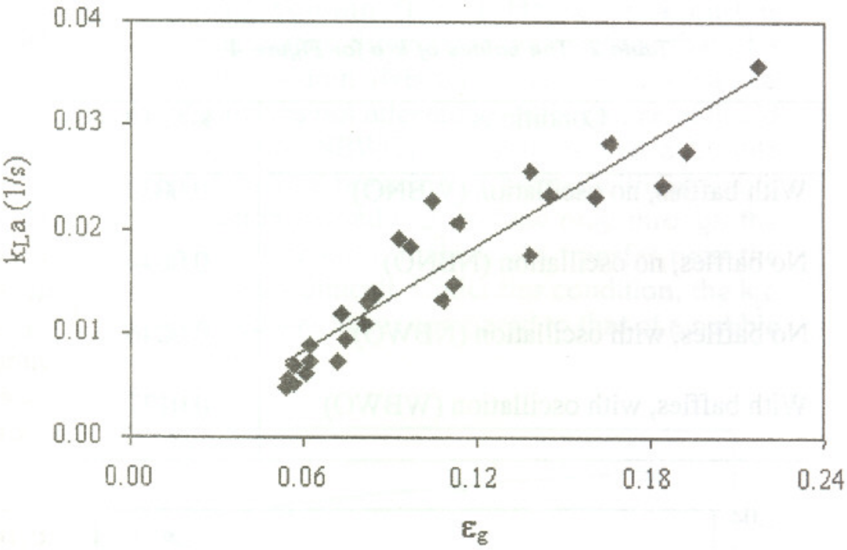


Figure 7. Relation ship between k_La and ε_g for oscillatory baffled column

CONCLUSION

The experimental results described in this paper show that gas holdup and mass transfer in semi-batch operations are significantly improved in an oscillatory baffled column compared to a bubble column. Liquid oscillation alone does not have an effect on gas holdup and mass transfer, while orifice baffles alone lower gas holdup and mass transfer within the range used. When orifice baffles are inserted into the column, gas holdup and mass transfer improvements are a strong function of the amplitude and frequency of oscillation. Moreover, gas holdup and mass transfer are also increased with gas flow rate. For the bubble column, gas holdup and mass transfer are correlated as a function of superficial gas velocity, while for the oscillatory baffled column, gas holdup and mass transfer are correlated as a function of power density and superficial gas velocity. Mass transfer is also correlated as a function of gas holdup giving a linear relation for the range of this study. However, it is difficult to propose a general correlation that will predict gas holdup and mass transfer which will be valid for all types of contactors since each contactor has its own characteristic, depending on its geometrical configuration and operating conditions.

NOTATIONS

a	Constant
BC	Bubble column
C	Concentration of dissolved CO_2, $kmol/m^3$
C*	Saturated concentration of dissolved CO_2, $kmol/m^3$
C_D	Orifice discharge coefficient (usually taken as 0.7)
D	Inside diameter of column, m
D_o	Inner diameter of baffle (orifice), m
f	Oscillation frequency, Hz
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_g	Volumetric gas flow rate, m^3/s
Re_o	Oscillatory Reynolds number
St	Strouhal number
ST	Stirred tank/vessel
t	Time, s
U_g	Superficial gas velocity, m/s
V_l	Liquid volume of the column, m^3
V_g	Gas volume of the column, m^3
x_o	Center to peak amplitude of oscillation or haft of stroke length, m
a	Ratio of orifice area to column area
e_g	Gas holdup
r	Liquid density, kg/m^3
m	Liquid viscosity, kg/(m·s)
w	Angular frequency of oscillation (2pf), rad/s

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