Mixing Time, Circulation Time and Liquid Circulation Velocity in a Modified Airlift Loop Reactor with Double Draft Tubes

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Abstract

The liquid mixing time, circulation time, and circulation velocity in the riser and two downcomers of a modified airlift loop reactor with double draft tubes were investigated. The mixing parameters found with using tracer technique in a column of 18.5cm in diameter, 90cm in height, and two concentric draft tubes of 14 and 8.5cm in diameter and 82cm in height respectively. The tracer injection method and impulse response was used to find the mixing parameters. The mixing times decreased with superficial gas velocity, with a power correlation. The exponent values were -0.194, -0.197 and -0.164 for riser, inner and outer downcomers respectively, which shows the lower values of mixing time for double draft-tube configuration compared to conventional ALR. The mixing parameters and circulation velocity are compared for different part of the column. For all injections points, the similar results were achieved in all sections. An ascending trend of circulation velocity with the increase of superficial gas velocity was seen. The circulation velocity in riser, inner and outer downcomers varied with an exponent of 0.235, 0.145, and 0.177 with superficial gas velocity respectively. The liquid circulation velocity in the outer downcomer showed higher values, because of higher wall effects and losses, than the inner one.

Keywords: Modified Airlift Loop Reactor, Double draft tubes, Mixing time, Circulation time, Liquid circulation velocity.

Introduction

Airlift loop reactors (ALR) have emerged as one of the most promising equipments in chemical, biochemical and environmental operations. Its main advantages over conventional reactors include excellent contact among the gas-liquid-solid phases, ease of removal or replenishment of particles, reduced risk of blockage, less pressure drop with high heat and mass transfer rates, and good mixing properties at low energy consumption as the gas phase serves the dual function of aeration and agitation [1]. An ALR consists of four distinct sections: riser, downcomer, top and bottom [2]. The fluid circulates along a well defined path: upflow in the riser, downflow in the downcomers. The difference in hydrostatic pressure arising from the difference in dispersion density between these regions induces liquid circulation in the contactor, thus enhancing the macro-scale mixing of the liquid phase compared to that of bubble columns (BC) [3]. Many investigations have been done to change the flow behaviors and mixing in the bubble column, in order to enhance oxygen transfer and mixing. Each type of the loop reactor may be a favorable one for a certain field or application. Multiple (Modified) Airlift Loop Reactor (MALR) is the combination of loop reactor with BC, which could be varied in many ways [4]. Lu et al. (2000) developed a Modified Square Airlift Loop Reactor (MSALR). They investigated the effects of the ratio of height to diameter of draft tube (H_d/D_d), and the ratio of cross-sectional area of riser to downcomer (A_r/A_d) on gas holdup, liquid circulation velocity and mixing time in the MSALR. A comparison of these characters as well as the total volumetric mass transfer coefficient was carried out between MSALR and Round Airlift Loop Reactor (RALR). The results indicated

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that the hydrodynamics of MSALR was better and its characteristics of gas holdup and mass transfer surpass those of RALR; i.e., the average volumetric mass transfer coefficient is 40% larger [5]. A modified ALR with double net draft tubes was developed by Tung et al. (1997). A perforated sparger was located between the two draft tubes which were employed to break bubbles into smaller ones. The ALR mixing time was less than that of the bubble column [6]. Huang et al. (2000), proposed an aeration strategy for foam control in an ALR with double mesh draft tubes, and they reached up to 70% higher products [7]. Wang et al. (2002) used a MALR with different numbers of rectangular wire-mesh draft tubes and found that the draft tubes improved the liquid mixing and decreased the bubble coalescence, which resulted in a higher gas holdup in the ALR. In their proposed reactor, the mixing time reduced up to 30% in comparison with those of the conventional BC [8]. Bello et al. (1984) studied liquid circulation and mixing in three and four sizes of external-loop contactors and the concentric-tube type, respectively. For both types of airlift contactors, the liquid circulating linear velocity was found to be dependent on the cube root of the riser superficial gas velocity. For $0.11 \leq A_d/A_r \leq 0.69$, the measured liquid circulating linear velocities in the risers (Ug_r) were about 3-5 times greater (4-42cm/s) than the corresponding riser superficial gas velocities (1.37-8.6cm/s). It has been shown that the ratio of mixing time to circulation time, t_m/t_c, virtually was independent of (Ug_r), being only dependent on A_d/A_r by an exponent of 0.5, and with the coefficient of 3.5 for the concentric-tube airlift contactors and 5.2 for the external ALRs respectively [9]. Freitas et al. (1998) used a 60L concentric draft tube ALR with an enlarged degassing zone. By increasing air flow rate, a decrease in circulation time was observed while the effects of solids loading (from 0% to 40%v/v) and solid phase density (1016 and 1038kg/m^3) were negligible. They found that t_c increased with Ug_r with an exponent of -0.311 and -0.351 for low and high density beads, respectively. Mixing time decreased with air flow rate, increased with solids density, in the studied range, and presented a maximum for solids loading of approximately 20%v/v [10]. The behavior of a bioreactor is determined not only by the reactor geometry but also by its hydrodynamic properties. The analysis and description of the behavior of an ALR involves the study of parameters such as gas holdup, mixing and liquid velocity. It is necessary to get information about the interaction between these parameters and the operation and the design variables, in order to make a correct design of the airlift bioreactor [11].

Liquid circulation time (t_c): The time necessary to a liquid volume element to travel once around the riser-downcomer circuit. The mixing in BC is purely dispersive; whereas a definite liquid recirculation is superimposed on mixing by dispersion in ALR which leads to the characteristic decaying sinusoidal tracer-response pattern [9]. It is a direct measure of the residence time of the liquid and it represents a suggestive parameter for explaining the effect of the reactor geometry on the liquid circulation in the loop [12]. Mixing in circulation loops leads to a variation of circulation times, which can be described by a residence time model, with an average residence time equal to the circulation time. In an ALRs, the mixing time can be related to the circulation time. With a criterion for the mixing intensity of 95%, this results in a mixing time $t_m=(4-7)t_c$. This relation offers the possibility of calculating the mixing time by means of the circulation time [13]. In fact, the rate of t_m to t_c generally indicates the rate of mixing and hence can be taken as a measure of mixing efficiency [14]. On the basis of visual observations one can consider three flow patterns of the tracer particle in the separator:

- Flow pattern A: The tracer particle is entrained by the prevailing liquid flow directly into the downcomer. This corresponds to the lowest number of residence times of the tracer particle (about 5-10s). This regime can be observed mainly in an ALR with a working volume of 20L, in which the liquid level is closely above the riser and for other working volume at low air superficial velocities.

- Flow pattern B: The turbulent region is formed closely under the top of the draft tube in the lower part of the separator, especially for higher air flow rates, there an intensive mixing of liquid takes place. According to visual observations, the tracer particle sometimes reached this zone and was entrained by eddies and after a short circulating in this zone was entrained back into the downcomer without reaching the above zone of separator. This resulted in higher residence times of the particle (in average about 10-20s).
- Flow pattern C: The tracer particle is entrained up to the upper part of the separator, where it is hold for a longer time and then it is drawn along the wall into the downcomer. The consequence of this is pretty high residence times for the tracer particle (above 30s). This regime can be found especially in the case of the working volume of 50L and in a small extent for working volumes of 25 and 35L [15]. According to these different flows, the separation of values of residence times of the tracer particle corresponding to the direct 180˚ turn of particle from the riser to downcomer, was done. These t_c values could adequately mimic the values measured using pulse response methods. This suggests that these scatters of t_c values are mainly caused by the fluctuations of the liquid flow in the separator.

Liquid circulation velocity (U_l): The geometric of the reactor influences U_l (a key design parameter of ALR). Circulation in ALRs is induced by the difference in hydrostatic pressure between the riser and the downcomer as a consequence of the difference in gas holdup. When the gas flow rate is increased, the higher U_l increases the carry over of bubbles from the gas separator into downcomer; the carry over dampens the liquid flow by reducing the hydrostatic driving force, therefore the overall change in U_l is tempered [16]. The gas holdup in the riser and the volumetric mass transfer coefficients decreases with U_l. Therefore, it is very important to be able to accurately predict the liquid circulation rates or superficial velocity in order to have a good understanding of the operational performance and to achieve optimum design of these contactors for various applications [9]. It depends on the superficial gas velocity (U_{sg}):

$$U_l = \alpha U_{sg}^{\beta} \tag{1}$$

In which α is a function of the reactor geometry and properties of the liquid, whereas β is determined by the flow regime as well as by reactor geometry [16]. The liquid circulation velocity U_l was calculated experimentally by the following relation:

$$U_l = 2h_D / t_c \tag{2}$$

In which h_D is aerated height of the liquid, and t_c is circulation time [4]. A problem with many existing correlations for liquid circulation in ALRs is that they are not very successful for U_l prediction in anything other than the particular reactors used for obtaining those [16].

Liquid mixing time (t_m): An important parameter used frequently to represent mixing in reactors is t_m. It expresses the overall mixing property of liquid and a shorter t_m means less chance of a dead zone formed [12]. It is specific to the reactor design and scale-up, and is easy to measure and understand. Mixing time is defined as the time required achieving the desired degree of homogeneity (usually 90-95%) after the injection of an inert tracer impulse into the reactor. About 6-7 circulation loops were necessary to achieve 95% homogenization. The so-called parameter is degree of homogeneity (I) is given by:

$$I = (C - C_m)/C_m \tag{3}$$

Where C is the maximum local concentration and C_m is the mean concentration of tracer at complete mixing [11]. In fact the mixing time is another indicator of the degree of mixing, the higher the degree of mixing, the shorter t_m would be. The studies with tracer injection showed that the back mixing in the riser to be far stronger relative to the downcomer where there was strong mixing. Good mixing was also observed in the reactor head space region particularly above the downcomer where the fluid streams from the two risers met and reversed their flow direction. t_m in ALR with concentric draft-tube declines with increasing liquid volume in the head space region of the reactor [11]. Comparing BCs and concentric draft-tube internal loops with either one or two draft-tubes leads to systematically higher t_m relative to BC operation. In addition, the double draft-tubes configuration resulted in higher t_m than the single draft-tubes geometry, probably because of the extended liquid circulation path in the former [16]. The relationship between t_m and U_{sg} can be approximated by:

$$t_m = a\, U_{sg}^{b} \tag{4}$$

The constants "a" and "b" change with the experimental conditions [10]. Weiland (1984) found that when draft tube is not used (BC), the t_m at various U_{sg} is longer than in ALR [10].

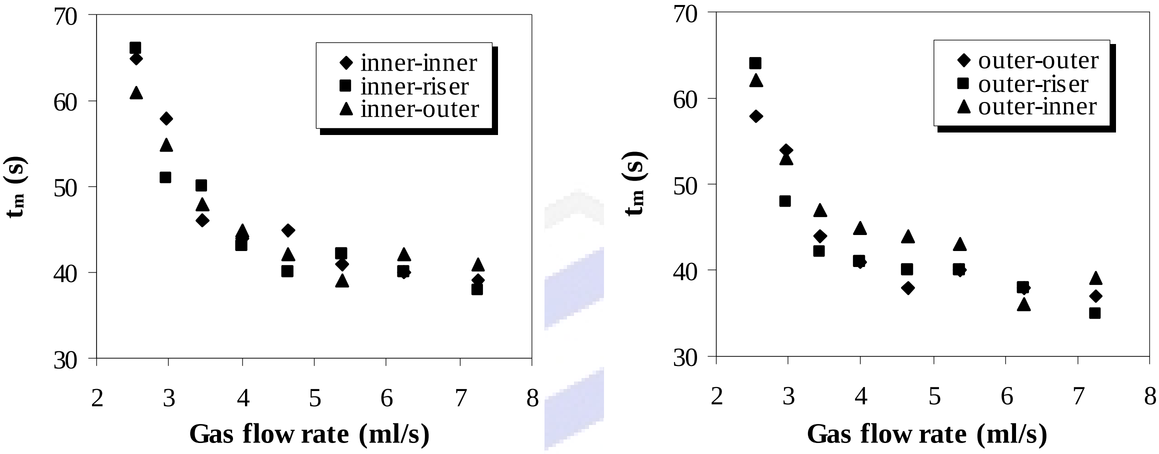
The aim of this work is to investigate the effect of using a modified ALR with two concentric double draft tubes on mixing, mixing time, circulation time and liquid circulation velocity in each section (riser and two downcomers) of the reactor.

Experimental

The reactor consists of a plexiglas cylindrical column of 18.5cm in internal diameter, 90cm in height, and two concentric draft tubes, 14 and 8.5cm in internal diameter and 82cm in height respectively. This structure resulted in a riser and two downcomers (inner and outer downcomer). A vertical space of 5cm was provided between the bottom of the column and the draft tubes to allow liquid recirculation. Tap water and compressed air at ambient temperature of 20°C are used as the working fluids. Air was sparged in to the annulus of the concentric draft tubes through 8 holes of 0.3mm in diameter. The air flow rate was measured by a calibrated rotameter before entering the reactor. In order to measure U_l and t_m, 50ml of saturated solution of NaCl, as a tracer, was injected (nearly ideal impulse) at the top of each section at each run. The concentration (conductivity) of tracer was determined by a conductivity-meter (Jenway; England). This method is widely applied on a small scale. The advantages are the simplicity of the method and the fast response characteristics of the conductivity probe. For experiments with large-scale airlifts the method is useless. Large volumes of tracer liquid are needed (100-500dm^3 for a 100m^3 ALR) and the gas bubbles in the airlift interfere with the measuring probe. Besides, the addition of an electrolyte and the related increase of osmotic pressure can lead to a change in rheological parameters of the broth and to a change in growth conditions [13]. The t_c, the distance between adjacent tracer output peaks, was directly determined from the response curves and converted to U_l from knowledge of the circulation path (dimensions of the contactor). The mixing time or blending time is defined as the time required achieving the desired degree of homogeneity (usually 90-95% of final value) after the injection of an impulse tracer into the reactor. The calculation of t_m for 95% difference between the final and instantaneous tracer concentration can be done directly from the tracer response curve in a very straight forward manner [16]. Before any data was taken, aeration was carried out over a longer period of time to ensure that a steady flow distribution was established in the airlift reactor. On the basis of repeated measurements and the uncertainties, an average error of ±5% was assigned to the measured values

Results and discussion

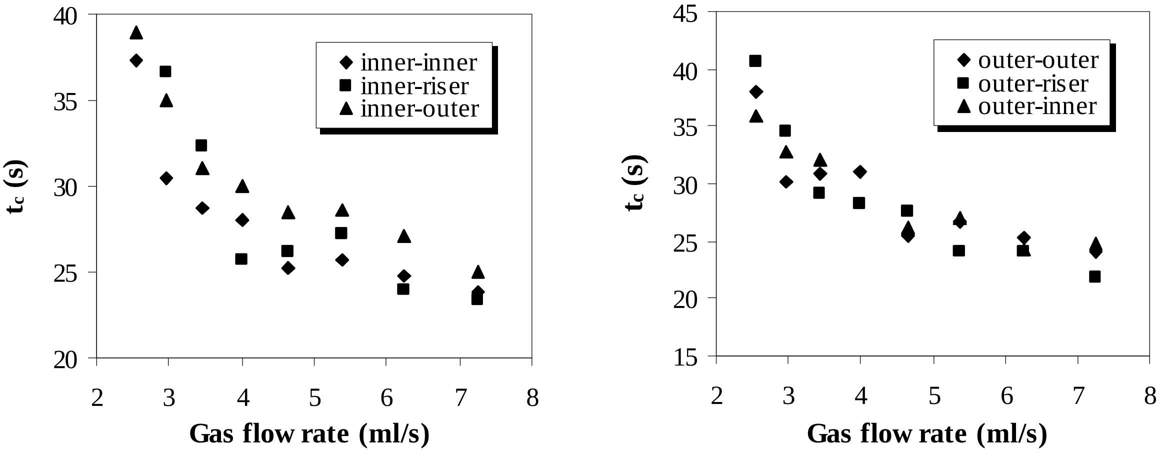
Liquid mixing time: The tracer was injected at the top of each section and its concentration was measured. In low air flow rates, an increase in U_{sg} leads to a significant improvement of the liquid circulation (Figure 1). Liquid moves more often to the degassing zone where most of the mixing takes place, due to the ring vortices formed above the draft tubes. In higher air flow rates, there is no significant improvement on circulation with the increase of superficial gas velocity, because of the driving force between riser and downcomers, which results in a lower rate of decrease in t_m, due to re-circulation of bubbles from downcomers to riser. The t_m decreased with U_{sg}, for each section.



a) injection point: inner downcomer **b) injection point: outer downcomer**

Figure 1: Mixing time versus air flow rate

Liquid circulation time: The effect of air flow rate on t_c were shown in Figure 2. It decreases with air flow rate. In the range of low air flow rates, circulation time is a strong function of the superficial gas velocity. After certain value, it stabilizes and its dependence on air flow rate becomes weak. For low air flow rates, downcomer's gas holdup is near zero and an increase in U_{sg} leads only to the increase of riser gas holdup. Therefore, the difference between riser and downcomer gas holdup (the driving force for liquid circulation) becomes larger, liquid velocity increases accordingly and circulation time decreases.

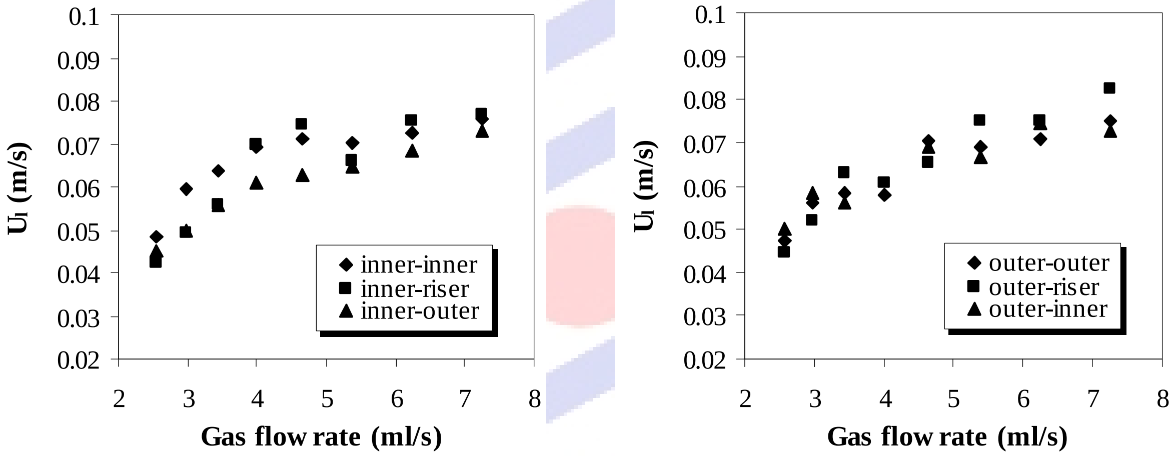


a) injection point: inner downcomer **b) injection point: outer downcomer**

Figure 2: Circulation time versus air flow rate

At high airflow rates, when superficial gas velocity is increased, both riser and downcomer gas holdup increase and its difference presents only a little reduction. The differences in t_c in the uniform bubbly flow and transition flow regimes are directly related to downcomer's holdup.

Liquid circulation velocity: The mixing process in ALR consists of back mixing and axial dispersion occurred respectively at the top and bottom deflection zones and in the riser/downcomer spaces. Mixing in riser and downcomer is caused by axial dispersion due to turbulence and differential velocities of gas and liquid phases [4]. Liquid circulation velocity impacts upon mixing and liquid phase dispersion, affects gas holdup, mass transfer and the extent of shear in the reactor. U_l increases with gas flow rate and an ascending trend of liquid circulation velocities could be seen (Figure 3). There is an initial range of U_{sg} in which the U_l is more sensitive to the increase of the air flow rate and, then a range in which a small increase in U_l is observed. It is related, essentially, to the difference between riser and downcomers gas holdup, which leads to the difference in hydrostatic pressure, responsible by the liquid flux.



a) injection point: inner downcomer **b) injection point: outer downcomer**

Figure 3: Liquid circulation velocity versus airflow rate

The calculated exponents "β" and "b" based on equations 1 and 4 and experimental results, were shown in Table 1. It could be seen that the exponents were in a good agreement for each section being measured, during both injection in the inner and outer downcomers. The U_{sg} is proportional to $U_l^{1/3}$ in ALR, based on working of Bello et al. (1984) [9]. The increase in liquid circulation velocity in MALR showed a slower slope than ALR with a single draft tube. The existence of two downcomers, which caused more bubbles recirculated to the downcomers at low values of U_{sg}, therefore the driving force for liquid circulation become weaker and it could be seen lower rate of increase and liquid circulation velocity in MALR than ALR. Freitas et al. found that "b" is equal to -0.417 for an ALR with one draft tube [10]. The ALR with double draft-tubes illustrates higher values compared to the conventional ALR with one draft-tube. The double draft-tubes configuration resulted in higher t_m than the single draft-tube geometry, probably because of the extended liquid circulation path in the former. The mixing process in ALRs consists of back mixing and axial dispersion occurred respectively at the top and bottom deflection zones and in the riser/downcomer space. Mixing in riser and downcomer is caused by axial dispersion due to turbulence and differential velocities of gas and liquid phases [4].

Table1. Experimental values of exponent "β" (eq. 1) and "b" (eq. 4)

Injected point	Measurement point	β	b
Inner downcomer	Inner downcomer	0.145	-0.197
	Riser	0.235	-0.194
	Outer downcomer	0.177	-0.164
Outer downcomer	Inner downcomer	0.168	-0.180
	Riser	0.223	-0.210
	Outer downcomer	0.166	-0.170

In the same gas flow rate, the riser superficial liquid velocities were higher than the downcomers, although the outer downcomer cross sectional area was about two times more than the inner one, it could be seen that liquid circulation velocities in the outer downcomer are lower than the inner one. This can be elucidated by the fact that higher losses and wall effects occur in the outer downcomer than the inner one, which result in low values of the outer downcomer liquid circulation velocities.

Conclusion

In the present work, new data was reported for two-phase air-water flow in an novel geometry air lift reactor with double draft tubes (MALR). The obtained mixing parameters and circulation velocity were compared for different sections of the column. For all injections points, the similar results were achieved in all sections. The liquid mixing times decreased with superficial gas velocity for riser, inner and outer downcomer, and the exponent values were about -0.197, -0.194 and -0.164, respectively, which presents lower values of t_m for double draft-tube configuration compare to conventional ALR. An ascending trend of liquid circulation velocity with the increase of superficial gas velocity was observed. The riser, inner and outer downcomer liquid circulation velocities were increased with superficial gas velocity by an exponent of 0.235, 0.145 and 0.177, respectively, which were lower rate of increase of U_l in MALR than ALRs. Although the outer downcomer cross sectional area was double in value than the inner one, there were lower liquid circulation velocities in the outer downcomer than the other one, because of the higher wall effects and losses in the outer downcomer than the inner one.

References

1. Zhang, T., Wang, T., and Wang, J., "Mathematical modeling of the residence time distribution in loop reactors", *Chem. Eng. Proc.*, **44**, 1221 (2005).
2. Lu, W. J., and Hwang, S.J., "Liquid mixing in internal loop reactor", *Ind. Eng. Res.*, **33**, 2180 (1994).
3. Popovic, M. K., and Robinson, C. W., "Mass transfer studies of external loop airlift reactors and a bubble column", *AICHE J.*, **35** (3), 393 (1989).
4. Lu, X., Ding, J., Wang, Y. and Shi, J., "Comparison of the hydrodynamics and mass transfer characteristics of a modified square airlift reactor with common airlift reactors", *Chemical Engineering Science*, **55**, 2257 (2000).
5. Ghoes, T. K., Fiechter, A., and Blakebrough, N., Advances in biochemichal engineering, Springer-verlag, berlin Heideberg, Newyork, p. 121 (1979).
6. Tung, H. L., Chiou, S. Y., Tu, C. C., and Wu, W. T., "An airlift reactor with double net draft tubes and its application in fermentation", *Bioprocess. Eng.*, **17**, 1 (1997).
7. Huang, T. K., Wang, P. M. and Wu, W. T., "Cultivation of Bacillus thuringiensis in an airlift reactor with wire mesh draft tubes", *Biochemical Engineering Journal*, **7**, 35 (2001).

8. Wang, P. M., Huang ,T. K., Cheng, H. P., Chien, Y. H. and Wu, W. T., "A modified airlift reactor with high capabilities of liquid mixing and mass transfer", *J. Chem. Eng. Japan*., **35** (4), 354 (2002).
9. Bello, R. A., Robinson, C. W., and Moo-Young, M., "Liquid circulation and mixing characteristics of airlift contactors", *Can. J. Chem. Eng*., **62**, 573 (1984).
10. Freitas, C., and Teixeira, J. A., "Hydrodynamic studies in an airlift reactor with an enlarged degassing zone," *Bioprocess. Eng*., **18**, 267 (1998).
11. Michael, J.C., and M. Gluz, "Bioreactors, Airlift Reactors, in *The Encyclopedia of bioprocess technology* (Flickinger, M. C., and S. W. Drew, editors)," 1, 320, John Wiley & Sons Inc., USA. (1996).
12. Bando, Y., Hayakawa, H., and Nishimura, M., "Effects of equipment dimensions on liquid mixing time of bubble column with draft tube," *J. Chem. Eng. Japan*., **31** (5), 765 (1998).
13. Riot, K., and Tramper, S., *Basic bioreactor design*, Marcel Deckker, Inc., Newyork, Basel, Hong Kong, P. 183 (1979).
14. Hari, M., and Tan, R. B. H., "Mixing in circulating flows", *J. Chem. Eng*., **73**, 29 (1999).
15. Dolgos, O., Klein, J., Vicente, A. and Teixeira, J. A., "Behaviour of dual gas-liquid separator in an internal-loop airlift reactor - effect of top clearance", proceedings of *The 28th Conference SSCHE*, Tatranske, Matliare (SK), pp. 21-25 (2001).
16. Chisti, M. Y., Moo-Young, M., "Airlift reactors: characteristics, applications and design considerations", *Chem. Eng. Comm*., **60**, 195 (1987).