Korean J. Chem. Eng., **23**(6), 881-887 (2006)

Hydrodynamics and mass transfer behavior in multiple draft tube airlift contactors

Nalinee Tunthikul, Porntip Wongsuchoto and Prasert Pavasant†

Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, 10330, Thailand

(*Received 23 February 2006 • accepted 14 July 2006*)

Abstract−The draft tube configuration significantly affected the performance of an airlift contactor. The multiple draft tube configuration was demonstrated to give a better gas-liquid mass transfer when compared with a conventional one-draft-tube system. The airlift with a larger number of draft tubes allowed a higher level of bubble entrainment, which rendered a high downcomer gas holdup. This resulted in a higher overall gas holdup in the contactor. Liquid velocity was also enhanced by increasing the number of draft tubes. The ratio between downcomer and riser cross sectional areas, A_d/A_r, had a great effect on the system performance, where a larger A_d/A_r led to a lower downcomer liquid velocity and smaller quantity of gas bubbles being dragged into the downcomer. This resulted in low gas holdup, and consequently, low gas-liquid interfacial mass transfer area, which led to a reduction in the overall volumetric mass transfer coefficient. The presence of salinity in the system drastically reduced the bubble size and subsequently led to an enhancement of gas entrainment within the system. As a result, higher gas holdups and gas-liquid interfacial area were observed, and hence, a higher rate of gas-liquid mass transfer was obtained.

Key words: Bubble, Reactor, Salinity, Gas Holdup, Liquid Velocity

INTRODUCTION

The airlift contactor is a pneumatic device with potential to be further developed for many applications especially in the biotechnological industry [Camacho et al., 2001; Mirón et al., 2003; Jianping et al., 2005; Krichnavaruk et al., 2005; Silapakul et al., 2005]. Past studies which examined large-scale airlift contactors were mostly performed in a conventional airlift configuration with small diameter (column diameter not larger than 45 cm) [Koide et al., 1984; Merchuk et al., 1994; Russell et al., 1994; Shamlou et al., 1995; Choi et al., 1996]. The development of actual airlift applications requires fundamentals on the performance of large scale systems whose behavior could be much different from laboratory scale experiments. For instance, Heiijnen et al. [1997] demonstrated that faster liquid velocity was obtained in a large scale airlift (4.5 m diameter, 284 m^3 volume) operated within the same conditions with a small system (0.2 m diameter, 0.4 m^3 volume). This was attributed to the lower wall friction generated in the larger scale airlift contactors than the smaller systems. This finding agreed well with that reported by Blažej et al. [2004] who also stated that gas holdup increased with an increase in reactor scale under the same operating condition.

Our experience [Wongsuchoto and Pavasant, 2004] revealed that it was difficult to obtain good distribution of bubbles in an airlift with large riser due to the existence of internal liquid circulation in the riser itself. Therefore, a multiple draft tube airlift system was herewith proposed as a potential configuration that could facilitate the design and operation of such large-scale airlift reactors. In the multiple draft tube configurations, each draft tube was connected with individual gas sparger that helped distribute gas bubbles within the contactor, and hence, the gas-liquid mass transfer was improved. Due to the ease of construction, Jianping et al. [2005] recently reported success in applying a multiple draft tube, large scale, airlift bioreactor for nitrification reaction.

Experiments in this work were performed in a 170 L airlift contactor with 0.69 m in column diameter. Three configurations of draft tubes--single (conventional type), three, and four draft tubes--were compared in terms of hydrodynamic and mass transfer properties. Three ratios between downcomer and riser cross sectional areas (1.27, 2.03 and 2.82) were examined with the superficial gas velocity varied in the range from 0.4 to 2 cm/s. The effect of salinity on the performance of the system was also determined.

EXPERIMENTAL

1. Apparatus Setup

Experiments were carried out in a large-scale internal-loop airlift with a working volume of 0.17 m^3. The setup of the airlift system is shown in Fig. 1 (one draft tube configuration). The airlift column (or tank) and draft tubes were made of transparent acrylic plastic in

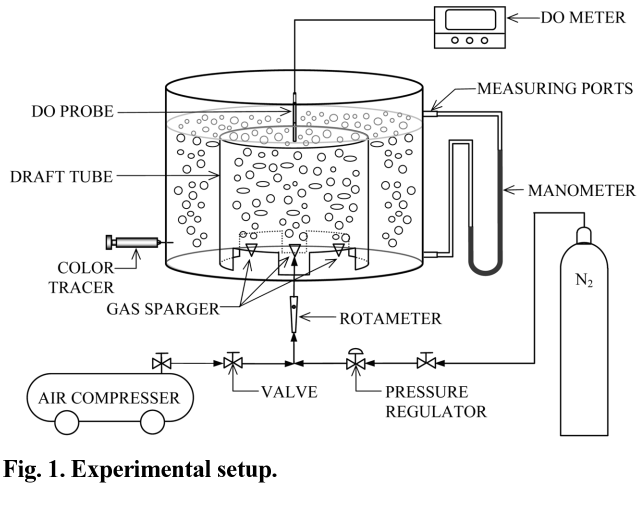

Fig. 1. Experimental setup.

---

†To whom correspondence should be addressed.
E-mail: prasert.p@chula.ac.th

Table 1. Specifications of airlift contactors

Ref. no.	N_{DT}	D_{DT} (m)	A_d/A_r (-)	Description
ALC-1	1	0.40	2.03	Single draft tube
ALC-2	3	0.23	2.03	Three draft tubes
ALC-3	4	0.23	1.27	Four draft tubes
ALC-4	4	0.20	2.03	Four draft tubes
ALC-5	4	0.18	2.82	Four draft tubes

order to facilitate the observation. The main column was cylindrical with a diameter of 69 cm and a height of 56.5 cm, and was equipped with measuring ports for the measurement of pressure drop, which was used to determine the downcomer gas holdup, ε_{gd}. Draft tubes with a height of 40 cm were installed in the column where a clearance between the column base and the bottom of the draft tube was fixed at 5 cm. Several configurations of draft tubes, i.e., the number of draft tube and their sizes, as indicated in Table 1, were investigated. Experiments were operated in a semi-batch operation where a continuous air flow was supplied through porous spargers installed in the middle of each draft tube into the liquid-filled column. The unaerated liquid height was controlled at 7 cm above the top of draft tubes. For all experiments, the gas flow rate was regulated by calibrated rotameters and measured in terms of superficial velocity, u_{sg} (in the range of 0.4-2 cm/s). The experiments were operated with either tap water or seawater as liquid phase. A salinity level of the seawater in the range from 15 to 45 ppt was investigated.

2. Measuring Methods

2-1. Gas Holdups

The overall gas holdup, ε_{go}, was determined by the volume expansion method, while the downcomer gas holdup, ε_{gd}, was estimated by measuring the pressure difference between the two measuring ports of the column via a U-tube manometer. The riser gas holdup, ε_{gr}, was computed from the overall and downcomer gas holdups. Details of the measurement as provided in Choi et al. [1996] should be consulted.

2-2. Liquid Velocity

Liquid velocity was measured by using the tracer injection method [Gopal and Sharma, 1982]. The pressure taps were employed as injection points of the color tracer and the traveling time of color tracer between the two points in the contactor was measured for the calculation of liquid velocity.

2-3. Gas-liquid Mass Transfer

The overall volumetric mass transfer coefficient (k_La) was determined by the dynamic method [Wongsuchoto and Pavasant, 2004]. A dissolved oxygen meter (Jenway 9300) was used to record the changes in concentration of O_2 in a batch of liquid that had previously been freed of O_2 by bubbling through with N_2.

RESULTS AND DISCUSSION

1. Influence of Configuration on Airlift Contactor Performance

Three configurations of airlift contactors were investigated: ALC-1 (1 draft tube), ALC-2 (3 draft tubes), and ALC-4 (4 draft tubes). A schematic diagram of the airlift systems with various designs of draft tubes is shown in Fig. 2. In this section, all airlifts had the same downcomer to riser cross sectional area ratio (A_d/A_r) of 2.03 and salinity of 30 ppt. Note that it was difficult to have the two draft tubes configuration as the resulting downcomer area would be highly uneven.

1-1. Effect of Airlift Configuration on Gas Holdups

From the experimental results depicted in Fig. 3(a), ALC-1 occupied the lowest overall gas holdup. Higher gas holdup was observed as the number of draft tubes increased (ALC-2 and ALC-4). Similar findings were noticed for downcomer and riser gas holdups as displayed in Figs. 3(b) and (c), respectively. Visual observation suggested that bubble size was slightly larger in ALC-1 than those in ALC-2 and ALC-4, respectively. These slightly large bubbles might be the result of the bubble coalescence due to the self-contact between individual bubbles. Our previous report [Wongsu-

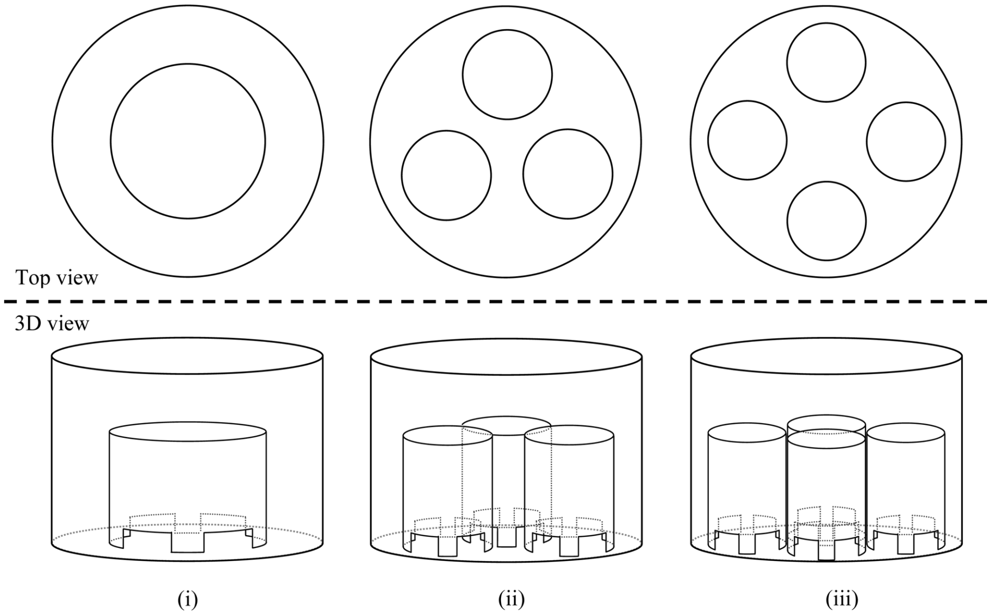

Fig. 2. Airlift configurations: (i) one draft tube, (ii) three draft tubes, (iii) four draft tubes.

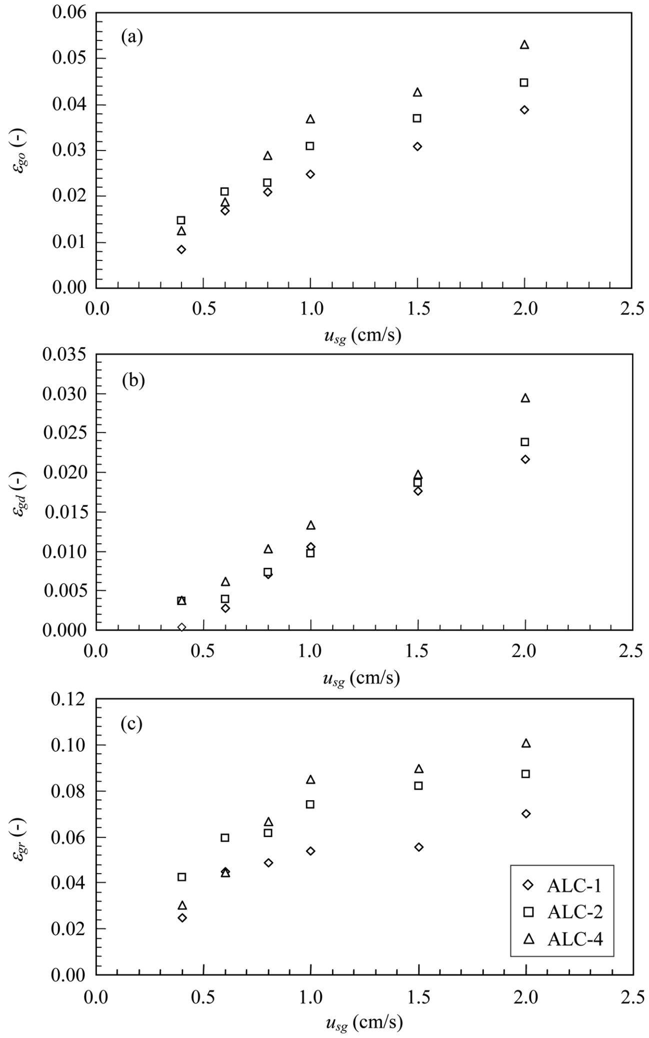

Fig. 3. Effect of airlift configurations on gas holdups (A_d/A_r=2.03, SW30).

choto and Pavasant, 2004] showed that, in a system with a large riser, the local internal liquid circulation (within the riser itself) would play a significant role in controlling the hydrodynamics in the reactor. This local internal circulation might promote bubble collision and coalescence leading to large bubbles which could escape from the liquid surface more easily than small ones, and therefore a smaller riser gas holdup became apparent. In ALC-4, the four draft tube configuration provided more connecting area between downcomer and riser, which allowed easier recirculation of bubbles between these two sections, and therefore a much larger fraction of small bubbles was entrained into the downcomer than those in ALC-1 and ALC-2. To clarify this point, the following equation was introduced for the calculation of the ratio between the circumference of the draft tube and the riser cross sectional area, ϕ:

$$\left.\begin{aligned} &\phi = 2\pi R/\pi R^2 \\ &\phi_{ALC\text{-}1} = 0.1013 \\ &\phi_{ALC\text{-}2} = 0.1939 \\ &\phi_{ALC\text{-}4} = 0.2000 \end{aligned}\right\} \qquad (1)$$

where R is the radius of the draft tube, and ϕ represents the opportunity for the small bubbles to be dragged down into the downcomer by the liquid flow. In ALC-1, ϕ was small, indicating that there was only a small chance that bubbles moved down in the downcomer, and therefore a large fraction of small bubbles left the system at the liquid surface instead. In ALC-4 on the other hand, ϕ was the largest, hence providing more chance of small bubbles to be dragged down into the downcomer and causing a higher level of downcomer gas holdup. In addition, it is generally known that gas bubbles can be entrained into the downcomer when liquid velocity in downcomer is greater than the terminal bubble rise velocity. In this case, the liquid velocity in ALC-4 was the greatest (Fig. 4), followed by those in ALC-2 and ALC-1 at the same level of u_{sg}, respectively, and hence, this supports the findings on gas holdups as described above.

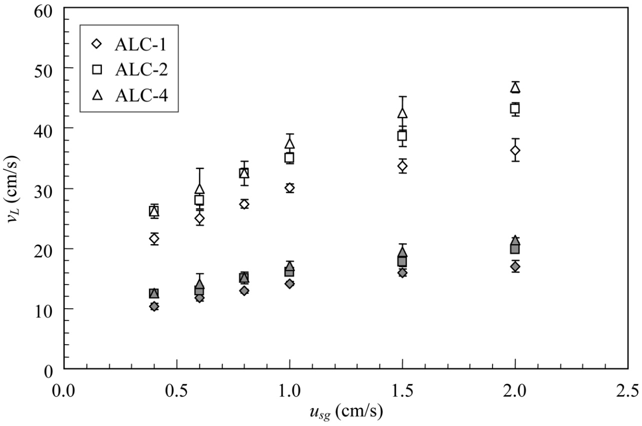

Fig. 4. Effect of airlift configurations on liquid velocities (A_d/A_r= 2.03, SW30) (filled symbols for downcomer and empty symbols for riser).

1-2. Effect of Airlift Configuration on Liquid Velocity

Although larger bubbles generated in ALC-1 tended to move faster than small bubbles in ALC-2 and ALC-4, the large riser area caused significant internal recirculation within the riser itself [Wongsuchoto and Pavasant, 2004]. This behavior was similar to that of the bubble column which led to a low riser liquid velocity (Fig. 4). On the other hand, the highest riser liquid velocity can be achieved from ALC-4, the airlift with the smallest draft tube diameter (at the same A_d/A_r with ALC-1 and ALC-2). In ALC-4, each draft tube was only one-fourth of that in ALC-1. This small riser diameter facilitated better liquid movement between riser and downcomer zones, and less internal recirculation within the riser was observed.

1-3. Effect of Airlift Configuration on Overall Volumetric Mass Transfer Coefficient

Fig. 5 illustrates that the configuration or the number of draft tubes in the airlift system (with constant A_d/A_r) significantly influenced the level of k_La. The airlift with one draft tube (ALC-1) was clearly shown to have an inferior level of k_La than the other two configurations, where the four draft tubes (ALC-4) was proven to exhibit the highest k_La. It was previously shown that ALC-1 occupied the smallest quantity of air and also with the lowest liquid velocity. Low liquid velocity suggested that there was a rather low level of gas bubbles in the downcomer (as seen in Fig. 3). In addition, a large, single draft tube did not provide adequate space for the return of the gas bubbles as some of the gas bubbles, particularly if they were in the middle of the draft tube, would not be dragged down to the down-

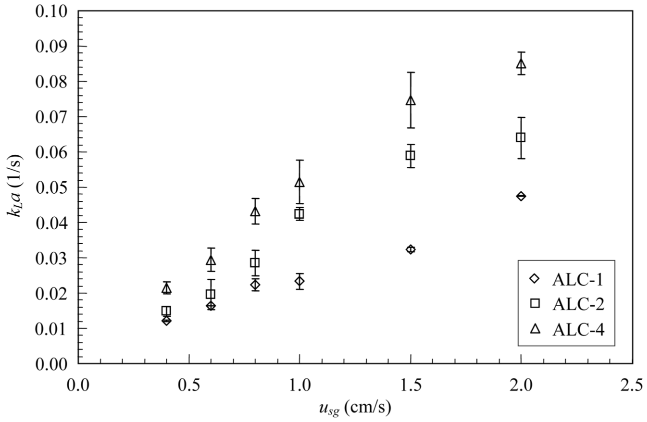

Fig. 5. Effect of airlift configurations on overall volumetric mass transfer coefficient (A_d/A_r=2.03, SW30).

comer but would leave the system at the liquid surface. In fact, the gas-liquid mass transfer depends more significantly on the riser gas fraction as it was still fresh with high oxygen content which enhanced the driving force for the transfer between gas and liquid. However, since the system employed in this work was rather short with a height of only 47 cm, gas bubbles in the downcomer were therefore still enriched in oxygen and could play a significant role in interfacial mass transfer. Hence, the loss of gas bubbles indicated the loss of total interfacial area between gas and liquid required for mass transfer, and therefore a lower k_La could be well observed. Next, it seemed that bubble size in ALC-1 was found to be larger than those in other configurations. This might be due to a greater coalescence of bubbles. These two reasons led to a reduction of specific mass transfer area (a) in the system and, consequently a decrease of k_La. In short, it can be concluded that, in case of a multiple draft tube configuration, an increase in the number of draft tubes enhanced the contacting surface between riser and downcomer, and thus, a large quantity of gas was able to recirculate within the system, leading to high interfacial area for mass transfer.

2. Influence of Downcomer to Riser Cross-sectional Area Ratio on Airlift Performance

Only the system with four draft tubes was selected for the investigation in this section as they were demonstrated to have the best performance with respect to the gas-liquid mass transfer. The details for the various configurations of the airlift contactor employed in this section are illustrated in Table 1: ALC-3, ALC-4, ALC-5.

2-.1 Effect of A_d/A_r on Gas Holdups

Fig. 6 demonstrates the influence of A_d/A_r on gas holdup where the operation with the largest downcomer (corresponding to A_d/A_r of 2.82 or ALC-5) was found to provide the lowest gas holdup in all regions of the airlift. As A_d/A_r became smaller, gas holdup increased. This was because bubbles seemed to be stream-lined and moved at a faster speed to the liquid surface in the system with large A_d/A_r (small riser), and therefore tended to leave the system instead of moving down the downcomer. This resulted in low gas holdup. In addition, Fig. 7 demonstrates that the liquid also moved faster in ALC with large A_d/A_r, and facilitated the disengagement of the bubbles as each bubble would have high velocity in riser. On the other hand, due to a large downcomer area, downcomer liquid velocity was rather low and was not enough to bring the bubbles downwards. As a result, a large fraction of gas bubbles were separated from the system at the top part. Hence, low level of gas holdup, both overall and in the downcomer, became obvious. On the other hand, in the system with smaller downcomer, such as ALC-3 and ALC-4, a faster downcomer liquid movement was obtained. This high liquid velocity induced more entrainment of gas bubbles into the downcomer, which enhanced the gas holdup in the downcomer and in the overall system.

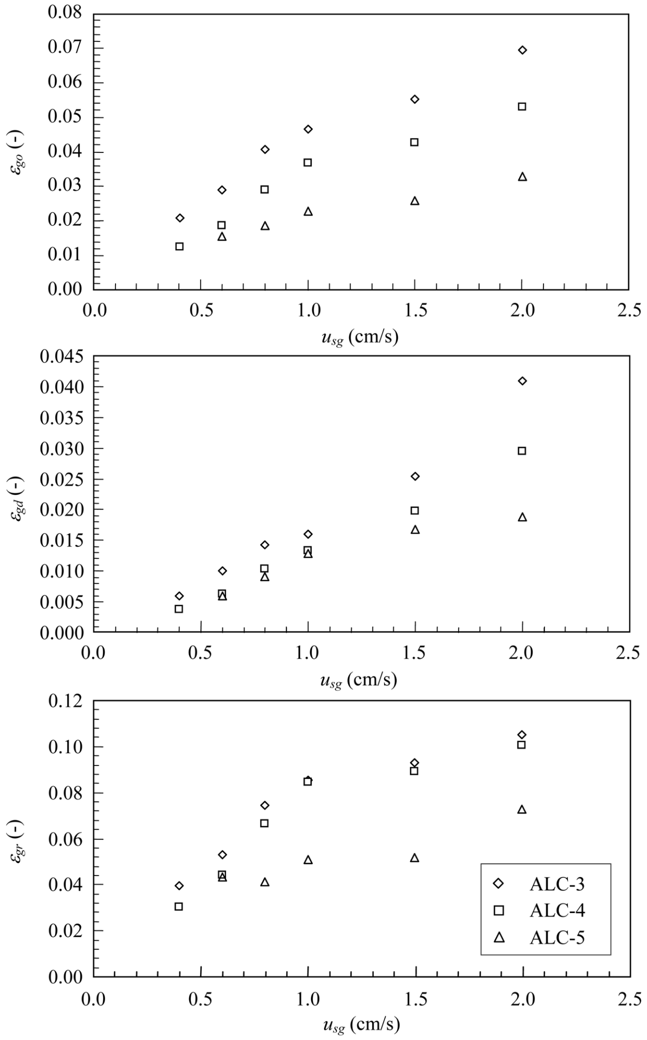

Fig. 6. Effect of A_d/A_r on gas holdups (SW30).

2-2. Effect of A_d/A_r on Liquid Velocity

Fig. 7 demonstrates that, although the riser liquid velocity increased with an enlarged A_d/A_r, the downcomer liquid velocities exhibited a reverse trend. The greatest value of downcomer liquid velocity was observed in the system with the smallest A_d/A_r (ALC-3), and the greatest riser velocity was in ALC-5. As the riser was rather small in ALC-5, gas bubbles seemed to be streamlined at the center of the draft tube and moved upwards at a very high speed. This induced high liquid velocity through energy and momentum transfer. As the liquid reached the top of the draft tube, it re-entered the system at the downcomer which was large in size. A mass balance showed that, with an enlarged entrance, the downcomer liquid velocity was quite low. In ALC-3, on the other hand, the reverse phe-

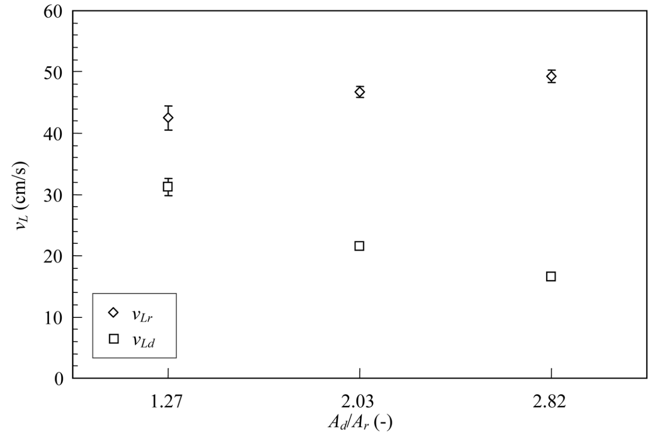

Fig. 7. Effect of A_d/A_r on liquid velocities (SW30, u_{sg}=2 cm/s).

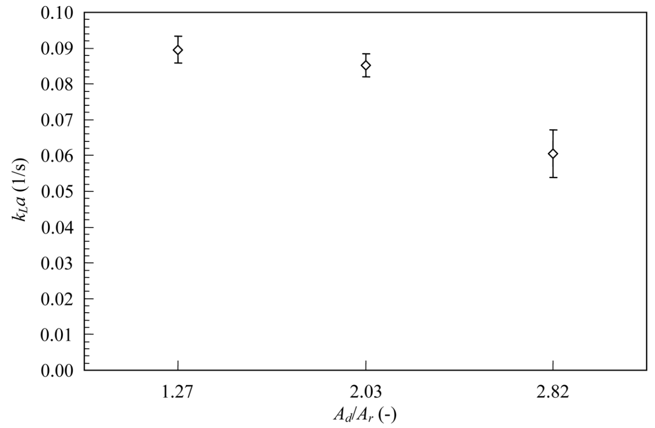

Fig. 8. Effect of A_d/A_r on overall volumetric mass transfer coefficient (SW30, u_{sg}=2 cm/s).

nomenon occurred. As the gas flowed more uniformly in the riser of such system, liquid moved at a lower speed. The re-circulating liquid then entered the downcomer, which in this case, had a smaller area size. Therefore, high downcomer liquid velocity was observed.

2-3. Effect of A_d/A_r on Overall Volumetric Mass Transfer Coefficient

An increase in A_d/A_r adversely affected the gas-liquid mass transfer rate as indicated in Fig. 8. This was not surprising as the airlift with large A_d/A_r was found to contain low gas holdup, which resulted in a small interfacial area between gas and liquid. Consequently, a low k_La was obtained as observed in ALC-5. On the other hand, ALC-3 allowed more bubbles to move into the downcomer, increasing the gas-liquid mass transfer area, and therefore a higher level of k_La was acquired. Although an airlift with a lower A_d/A_r tended to have a greater k_La than the system with a large A_d/A_r, it should be noted that the behavior of such system would approach that of the bubble column, i.e., a low riser liquid velocity and the existence of internal recirculation inside the draft tube could be well observed. A low liquid velocity would imply a higher chance of solid settlement, which could be detrimental for some applications involving three phases such as cell cultivation systems. In such case, a large A_d/A_r airlift system could then be useful as the appearance of a stronger liquid velocity could partially support the gas-liquid-solid mixing.

3. Influence of Salinity on Airlift Contactor Performance

The airlift system using a mixture of tap water and seawater at salinity of 15, 30, 45 ppt was compared. All experiments were performed in the airlift contactor with four 20 cm i.d. internal draft tubes where A_d/A_r was fixed at 2.03 (ALC-4). In the following discussion, "SW" is defined as seawater and the number following "SW" indicates the level of salinity in the unit of ppt, e.g., SW15=seawater at salinity of 15 ppt.

3-1. Effect of Salinity on Gas Holdups

Gas holdup in the airlift contactor was demonstrated to be influenced significantly by salinity levels. Fig. 9 illustrates that the system running with fresh tap water always had the lowest gas holdups. As the salinity increased, higher gas holdup was observed. However, the effect of salinity was only pronounced at high gas throughput condition (u_{sg}>1 cm/s).

It is known that salinity changed physical properties of the liquid by raising its surface tension, viscosity and density, and this strongly affected bubble size in the system [Prince and Blanch, 1990; Al-Masry, 1999]. High surface tension at high salinity level indicated stronger bubble surface force, which inhibited bubble coalescence. Hence, in the system with fresh tap water (low surface tension),

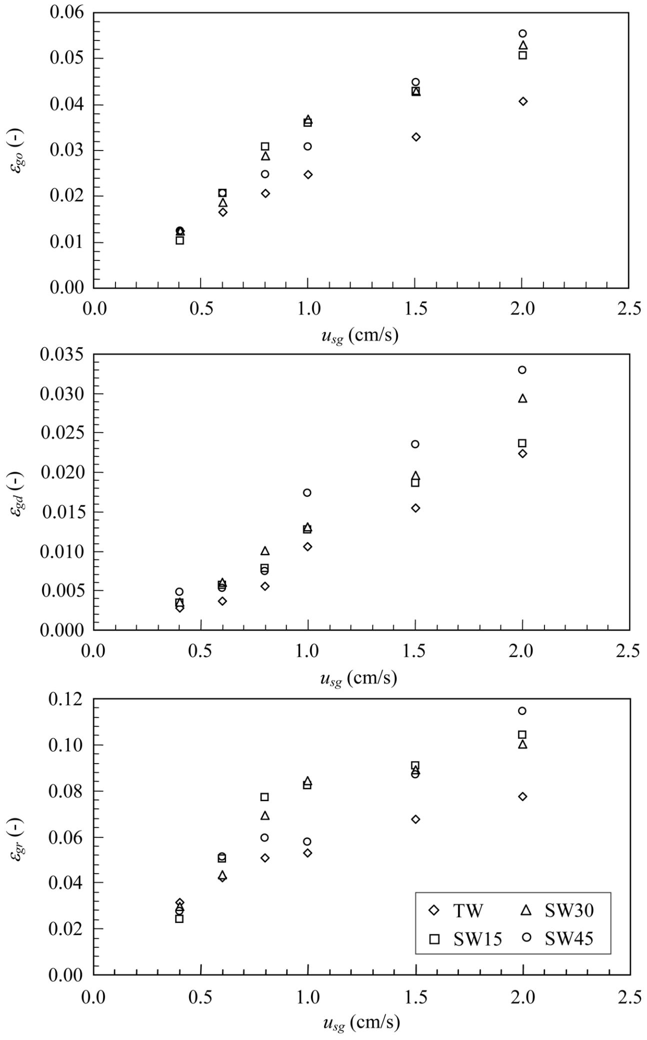

Fig. 9. Effect of salinity on gas holdups (ALC-4).

coalescence seemed to take place more intensively as a result of bubble-bubble interaction. This resulted in a larger bubble size. Large bubbles moved upwards rapidly due to high buoyancy force and caused a poor recirculation of bubbles within the system. This loss of bubbles reduced the total gas volume in the liquid resulting in low gas holdup.

The overall gas holdup in the airlift contactors operating at the various levels of salinity was found to increase with salinity level. Experiments revealed that the system with SW45 accommodated slightly higher gas holdup than the systems with SW30 and SW15, respectively, particularly at high gas throughput. This might be due to the existence of tiny bubble size in SW45, which facilitated the inducement of gas bubbles into the downcomer causing more bubbles to be recirculated within the system. Note that it was difficult to distinguish the sizes of bubbles obtained from the systems running with seawater at various salinity levels. Visual inspection alone could not identify the actual size with adequate accuracy. The system was also performed at a relatively high gas throughput, which was not suitable for measurement with a digital camera due to the bubble shading effects. The size of the bubbles inside the system was therefore estimated from observation.

3-2. Effect of Salinity on Liquid Velocity

Fig. 10 illustrates the effect of salinity on liquid velocities. It was observed that both riser and downcomer liquid velocities in the system with tap water were slightly higher than that obtained in the airlift with seawater. This was because the system with tap water was operated with larger bubbles which moved at a faster speed than smaller ones due to their high buoyancy force, and therefore induced through a momentum and energy transfer, a faster liquid movement. However, in this experiment, the difference in salinity levels (15, 30, and 45 ppt) was not found to have significant influence on liquid velocities.

3-3. Effect of Salinity on Overall Volumetric Mass Transfer Coefficient

The overall volumetric mass transfer coefficient, k_La, was clearly shown to be superior in the system operated with high salinity seawater rather than at low salinity (Fig. 11). Previous discussion demonstrated that liquid velocity was not significantly affected by the salinity. Therefore, it was expected that k_La would only be influenced by the changes in bubble characteristics which were altered as a result of changes in salinity. At high salinity, bubble size became small and this increased the interfacial area between gas and liquid. This meant that the specific surface area, “a,” increased with salinity. In fact, “k_L” was regulated by the difference between liquid and bubble velocities, and therefore the bubble size would also have effects on this parameter. In other words, larger bubbles would move at faster speed, and as the liquid velocity did not change with salinity, the system with larger bubbles would have had a larger difference in bubble and liquid velocities, resulting in a high “k_L”. This meant that the airlift system would have higher “a” but lower “k_L” at high salinity level than at low salinity. As the apparent k_La was a consequence of these two effects, higher k_La as a result of increasing salinity suggested that the effect of salinity on “a” could be more significant than that on “k_L”.

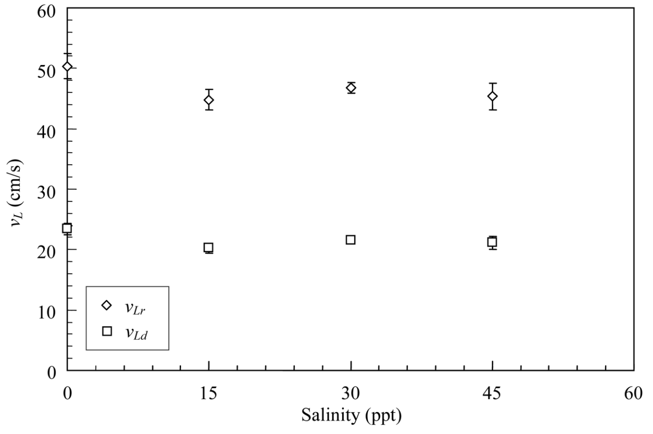

Fig. 10. Effect of salinity on liquid velocities (ALC-4, u_{sg}=2 cm/s).

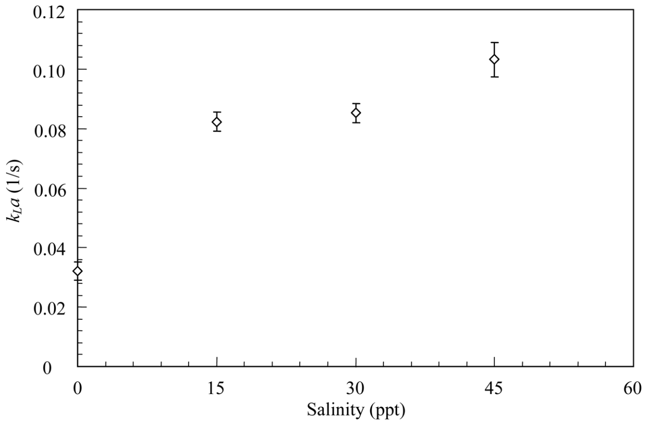

Fig. 11. Effect of salinity on overall volumetric mass transfer coefficient (ALC-4, u_{sg}=2 cm/s).

CONCLUSION

A new configuration of an internal loop airlift contactor with multiple draft tubes was proposed in this work. The hydrodynamics and mass transfer in a large-scale operation of the proposed configuration were observed at different u_{sg}, A_d/A_r and salinity levels and compared with a conventional single draft tube system. Increasing the number of draft tubes enhanced the connecting area between riser and downcomer leading to a better recirculation of fluid inside the airlift system. This also resulted in a higher gas-liquid interfacial area essential for mass transfer. Hence, the multiple draft tube

Table 2. Empirical correlations for overall volumetric mass transfer coefficient

	k_La (1/s)	Salinity (ppt)	R^2
ALC-1	$k_La=0.0251u_{sg}^{0.81}$	30	0.9815
ALC-2	$k_La=0.0363u_{sg}^{0.99}$	30	0.9669
ALC-3	$k_La=0.0556u_{sg}^{0.77}$	30	0.9894
ALC-4	$k_La=0.0495u_{sg}^{0.89}$	30	0.9872
ALC-5	$k_La=0.0277u_{sg}^{1.03}$	30	0.9793
ALC-4	$k_La=0.0175u_{sg}^{0.77}$	0	0.9717
ALC-4	$k_La=0.0438u_{sg}^{0.97}$	15	0.9861
ALC-4	$k_La=0.0600u_{sg}^{0.88}$	45	0.9784

airlift contactor was proven to be a potential system for the large-scale operation, especially in the case where a very large cross-sectional area is required. In this investigation, the overall volumetric mass transfer coefficients could be estimated relatively accurately by using the empirical correlations as proposed in Table 2.

ACKNOWLEDGMENTS

The authors wish to acknowledge the Thailand Research Fund for their financial support.

NOMENCLATURE

A_d : downcomer cross-sectional area [m^2]
a : specific gas-liquid interfacial area [m^2/m^3]
A_r : riser cross-sectional area [m^2]
D_{DT} : draft tube diameter [m]
k_L : mass transfer coefficient [m/s]
$k_L a$: overall volumetric mass transfer coefficient [1/s]
N_{DT} : number of draft tube
u_{sg} : superficial gas velocity [cm/s]
v_L : liquid velocity [cm/s]

Abbreviation

ALC : airlift contactor
ppt : part per thousand
SW : seawater
TW : tap water

Greek Letters

ε_{gd} : downcomer gas holdup [-]
ε_{go} : overall gas holdup [-]
ε_{gr} : riser gas holdup [-]

Subscripts

d : downcomer
r : riser

REFERENCES

Al-Masry, W. A., "Effects of antifoam and scale-up on operation of bioreactors," *Chem. Eng. Process*, **38**, 197 (1999).

Blažej, M., Kiša, M. and Markoš, J., "Scale influence on the hydrodynamics of an internal loop airlift reactor," *Chem. Eng. Process*, **43**, 1519 (2004).

Camacho, F. G., Grima, E. M., Mirón, A. S., Pascual, V. G. and Chisti, Y., "Carboxymethyl cellulose protects algal cells against hydrodynamic stress," *Enzyme and Microbial Technology*, **29**, 602 (2001).

Choi, K. H., Chisti, Y. and Moo-Young, M., "Comparative evaluation of hydrodynamic and gas-liquid mass transfer characteristics in bubble column and airlift slurry reactors," *Chem. Eng. J.*, **62**, 223 (1996).

Gopal, J. S. and Sharma, M. M., "Hydrodynamic and mass transfer characteristics of bubble and packed bubble columns with downcomer," *Can. J. Chem. Eng.*, **60**, 353 (1982).

Heijnen, J. J., Hols, J., van der Lans, R. G. J. M., van Leeuwen, H. L. J. M., Mulder, A. and Weltevrede, R., "A simple hydrodynamic model for the liquid circulation velocity in a full-scale two- and three-phase internal airlift reactor operating in the gas recirculation regime," *Chem. Eng. Sci.*, **52**(15), 2527 (1997).

Jianping, W., Xiaoqiang, J., Lei, P., Changlin, W. and Guozhu, M., "Nitrifying treatment of waste water from fertilizer production in a multiple airlift loop bioreactor," *Biochem. Eng. J.*, **25**, 33 (2005).

Koide, K., Iwamoto, S., Takasaka, Y., Matsuura, S., Takahashi, E. and Kimura, M., "Liquid circulation, gas holdup and pressure drop in bubble column with draught tube," *J. Chem. Eng. Jpn.*, **17**(6), 611 (1984).

Krichnavaruk, S., Loataweesup, W., Powtongsook, S. and Pavasant, P., "Optimal growth conditions and the cultivation of Chaetoceros calcitrans in airlift photobioreactor," *Chem. Eng. J.*, **105**, 91 (2005).

Merchuk, J. C., Ladwa, N., Cameron, A., Bulmer, M. and Pickett, A., "Concentric-tube airlift reactors: effects of geometrical design on performance," *AIChE J.*, **40**(7), 1105 (1994).

Mirón, A. S., Garć, M. C. C., Gómez, A. C., Camacho, F. G., Grima, E. M. and Chisti, Y., "Shear stress tolerance and biochemical characterization of *Phaeodactylum tricornutum* in quasi steady-state continuous culture in outdoor photobioreactors," *Biochem. Eng. J.*, **16**, 287 (2003).

Prince, M. J. and Blanch, H. W., "Transition electrolyte concentrations for bubble coalescence," *AIChE J.*, **36**(9), 1425 (1990).

Russell, A. B., Thomas, C. R. and Lilly, M. D., "The influence of vessel height and top-section size on the hydrodynamic characteristics of airlift fermentors," *Biotech. Bioeng.*, **43**, 69 (1994).

Shamlou, P. A., Pollard, D. J. and Ison, A. P., "Volumetric mass transfer coefficient in concentric-tube airlift bioreactors," *Chem. Eng. Sci.*, **50**(10), 1579 (1995).

Silapakul, S., Powtongsook, S. and Pavasant, P., "Nitrogen compounds removal in a packed bed external loop airlift bioreactor," *Korean J. Chem. Eng.*, **22**, 393 (2005).

Wongsuchoto, P. and Pavasant, P., "Internal liquid circulation in annulus sparged internal loop airlift contactors," *Chem. Eng. J.*, **100**, 1 (2004).