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Hydrodynamic and Mass Transfer Characteristics of External-Loop Airlift Reactors without an Extension Tube above the Downcomer

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Abstract−The effects of the horizontal connection length ($0.1 \le L_c \le 0.5$ m), the downcomer-to-riser cross-sectional area ratio ($0.11 \le A_d/A_r \le 0.53$) and the superficial gas velocity ($0.02 \le U_G \le 0.18$ ms^{-1}) on gas holdups in the riser and downcomer, the circulation liquid velocity, the mixing time, and the overall volumetric mass transfer coefficient were determined in external-loop airlift reactors without an extension tube above the downcomer [configuration (a)]. For otherwise fixed conditions, the absence of the extension tube strongly affected the hydrodynamic and mass transfer characteristics of external-loop airlift reactors. In contrast with the external-loop airlift reactor with the extension tube [configuration (b)], a large air pocket formed in the top horizontal connection and the surface aeration took place in the external-loop airlift reactor without the extension tube [configuration (a)]. As a result, the riser circulation liquid velocity in configuration (a) was slower than that in configuration (b). The riser and downcomer gas holdups, the mixing time and the overall volumetric mass transfer coefficient in configuration (a) were larger than those in configuration (b), respectively.

Key words: Airlift Reactor, Hydrodynamics, Mass Transfer, Horizontal Connection, Extension Tube

INTRODUCTION

Many investigators have been studying various airlift reactors because they have several advantages: simple design concept, high mixing performance, high mass transfer ability, good heat transfer, and low energy consumption. In particular, airlift reactors supply a mild culture condition since they have no moving parts. Therefore, in the case of the culture of shear-sensitive micro-organisms, the airlift reactor leads to a high yield of cells [Merchuk and Siegel, 1988]. Airlift reactors must have two main spaces (a riser and a downcomer): the former has an upward flow of fluid, the latter has a downward flow of fluid. As a result, a density difference between fluids in the two spaces takes place. A stable and well-defined fluid circulation occurs due to both the density difference and an airlift effect. In a comparison of bubble columns, airlift reactors have high mixing performance owing to the fluid circulation. On the other hand, it is well known that airlift reactors also have some disadvantages. The circulation liquid velocity suddenly decreases when viscous liquids are used. The mass transfer efficiency decreases when the circulation liquid velocity is too high. Use of airlift reactors has increased in various fields, such as aerobic fermentations, wastewater treatment, and three phase processes [Merchuk and Siegel, 1988].

Based on their configurations, airlift reactors can be classified into two groups: internal-loop and external-loop airlift reactors. An internal-loop airlift reactor contains a vertical baffle or a draft tube by which a loop channel for fluid circulation is formed in the reactor. An external-loop airlift reactor consists of two vertical tubes (a riser and a downcomer) which are connected by horizontal connections at the top and bottom. A distinctive difference between the two groups is the presence of the horizontal connections.

Based on the geometric configuration of the head region, external-loop airlift reactors can be subdivided into three types. One is the external-loop airlift reactor with a gas-liquid separator which joins the riser and the downcomer together and usually is a rectangular hexahedron shape [Merchuk and Stein, 1981; Merchuk, 1986; Kemblowski et al., 1993; Akita et al., 1994; Benyahia et al., 1996; Petrović et al., 1995]. The other is the external-loop airlift reactor which has both a top horizontal connection tube and an extension tube attached to the upper edge of the downcomer [Bello et al., 1984, 1985a, b; Popović and Robinson, 1987, 1988; Choi et al., 1990; Choi and Lee, 1993; Choi, 1996, 1997, 1999; Bentifraouine et al., 1997a, b; Gavrilescu and Tudose, 1997; Park, 1999]. The extension tube above the downcomer also acts as a gas-liquid separator. Another is the external-loop airlift reactor with a top horizontal connection tube and without the extension tube [Mercer, 1981; Mc-Mamamey et al., 1984; Snape et al., 1995; Bentifraouine et al., 1997a, b]. The design of the head region of airlift reactors - its gas-liquid separating ability and its hydraulic resistance - affects hydrodynamic and mass transfer characteristics of airlift reactors [Choi et al., 1995a, b]. Siegel et al. [1986] reported that the gas recirculation rate was largely determined by the gas-liquid separator's geometric configuration. Therefore, it can be expected that the hydrodynamic and mass transfer characteristics of the three types of external-loop airlift reactors are very different. However, there is scant literature which compared hydrodynamic and mass transfer characteristics in the three types of external-loop airlift reactors with identical dimensions. Only Bentifraouine et al. [1997a, b] compared the data of the riser circulation liquid velocity and the riser gas holdup which were obtained in the three types of external-loop airlift reactors with similar dimensions.

In addition, to date, only a few studies on hydrodynamics have

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been carried out in external-loop airlift reactors without an extension tube above the downcomer [configuration (a)]. Mercer [1981] investigated the effect of superficial gas velocity on circulation liquid rates, gas holdups, velocity of bubbles and the average bubble size in an external-loop airlift reactor with configuration (a). MacManamey et al. [1984] measured overall gas holdup in an external-loop airlift reactor with configuration (a) for several solutions. The effects of liquid properties and sparger design on the gas holdups and the downcomer circulation liquid velocity in an external-loop airlift reactor with configuration (a) were observed by Snape et al. [1995].

Therefore, in this study, the effects of the horizontal connection length, the superficial gas velocity and the downcomer-to-riser cross-sectional area ratio on the gas holdups in the riser and the downcomer, the mixing time, the circulation liquid velocity and the overall volumetric mass transfer coefficient were systematically investigated in external-loop airlift reactors without the extension tube above the downcomer. The experimental data obtained in this work were compared with the previous data [Choi and Lee, 1993; Choi, 1996] obtained in the same airlift reactor with the extension tube.

EXPERIMENTAL

A schematic diagram of the experimental set-up is shown in Fig.

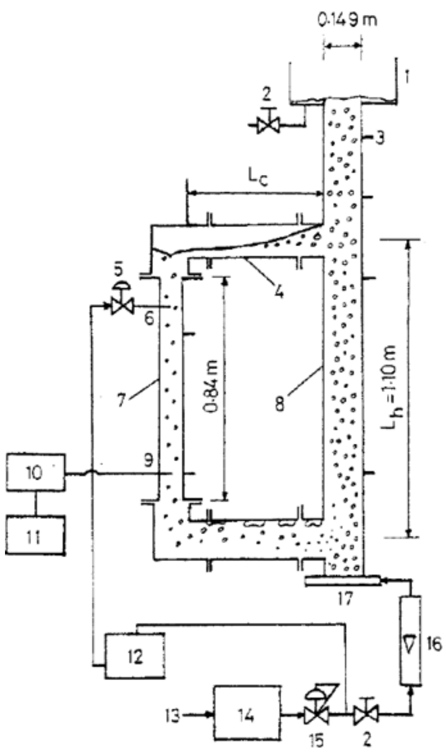

Fig. 1. Schematic diagram of experimental apparatus.

1. Weir box
2. Valve
3. Pressure tap
4. Top horizontal connection
5. Solenoid valve
6. Tracer injection tube
7. Interchangeable downcomer
8. Riser
9. Conductivity probe
10. Conductivity meter
11. Wave form analyzer
12. Salt solution tank
13. Air line
14. Air filter
15. Pressure regulator
16. Flowmeter
17. Gas sparger

Table 1. Dimensions of the experimental apparatus

Aerated liquid height	1.77 m
Riser i.d.	0.149 m
Height between horizontal connections	1.01 m
Horizontal connection i.d.	0.108 m
Horizontal connection length	0.10, 0.20, 0.30, 0.40, 0.50 m
Interchangeable downcomer i.d.	0.108, 0.079, 0.049 m
Interchangeable downcomer height	0.84 m

1. The external-loop airlift reactor used in the present work consisted of two vertical pipes (a riser and a downcomer), a top connection pipe and a bottom connection pipe. The top section above the top horizontal connection acted as a gas-liquid separator. All of the airlift reactor was made of acrylic transparent pipes and sheets with 0.006 m thickness. Main dimensions of the reactor are listed in Table 1. The reactor was obtained by elimination of the extension tube from the reactor of Choi and Lee [1993].

Tap water and air were used as the liquid and gas phases, respectively. Batch operation was employed with respect to the liquid phase. All experiments were carried out at room temperature and atmospheric pressure. Filtered air was fed into the riser through a gas sparger. The air sparger consisted of six tube spargers which were attached on the base plate [Choi et al., 1990]. Air flow rates were measured by a calibrated flowmeter. The superficial gas velocity (U_G), based on the cross-sectional area of the riser, varied over 0.02-0.18 ms^{-1}. The horizontal connection length (L_c) was changed in the range of 0.1-0.5 m. The cross-sectional area ratio of downcomer-to-riser (A_d/A_r) was varied by exchange of the interchangeable downcomer. The downcomer-to-riser cross-sectional area ratio ranged over 0.11-0.53.

To measure the local gas holdups in the riser, the downcomer and the top section, water manometers were installed at the upper and lower parts of those sections. The local gas holdups were determined by measuring the hydrostatic pressure differences in those sections [Choi, 1997].

The circulation time and the mixing time were determined by the tracer impulse method [Choi and Lee, 1993]. A conductivity probe was installed at the height of 0.307 m from the sparger. As a tracer, 10 cm^3 of 3 M potassium chloride solution was injected into the top of the downcomer. To obtain a transient tracer curve, the signal obtained by the probe and a conductance meter (YSI model 34) was stored on a wave form analyzer (Division of Analogic Co., Data 6000 model 611) with a sampling period of 0.1 s. The circulation time was determined as the mean time period between the two adjacent peaks in the transient tracer curve. The mixing time was measured as the time required to achieve 5% inhomogeneity throughout the reactor space. For the calculation of riser circulation liquid velocity, it was assumed that the effective circulating liquid volume (V_{EL}) was the liquid volume in the reactor space below the top section [Choi, 1996]. Then the riser circulation liquid velocity (U_{Lr}) could be calculated by using the effective circulating liquid volume, the circulation time and the gas holdup in the top section as follows:

$$U_{Lr} = \frac{V_{EL}}{A_r t_c} \quad (1)$$

$$V_{BL}=V_L-(1-\varepsilon_r)\,V_r \tag{2}$$

The overall volumetric mass transfer coefficient (k_La_L) was determined by the dynamic physical method. First, oxygen in the liquid was purged by dispersing nitrogen gas into the liquid until the oxygen concentration of the liquid became 0.3 ppm. After the nitrogen feed was stopped, air was introduced at a constant velocity. The transient dissolved oxygen concentration profile according to absorption time was measured by using both a polarographic dissolved oxygen probe (Yellow Springs Instruments, YSI 5739 with standard membrane) and a dissolved oxygen meter (YSI model 58). The profile data were simultaneously recorded on a waveform analyzer (Division of Analogic Co., Data 6000 model 611). A model based on constant gas phase composition and a well mixed liquid phase was used to calculate the overall volumetric mass transfer coefficient [Chisti and Moo-Young, 1988]. The overall volumetric mass transfer coefficient was determined by fitting the model equation to the experimentally determined transition curve. This was accomplished by analyzing the data with Powell's regression method. The overall volumetric mass transfer coefficient data here have been corrected to a common temperature of 20 °C by using Eq. (3) [Rand et al., 1975].

$$(k_La_L)_{20}=\frac{(k_La_L)_T}{(1.024)^{T-20}} \tag{3}$$

where the subscripts T and 20 denote values at any measurement temperature T and at 20 °C, respectively.

RESULTS AND DISCUSSION

For the external-loop airlift reactor without the extension tube, a large air pocket formed in the top horizontal connection as soon as air was sparged into the reactor (Fig. 2). After the initial formation of an air pocket, the size of the air pocket seemed to be almost constant because separation of bubbles from the fluid in the top horizontal connection made both an escape of a part of the air pocket to the top section and surface aeration from the air pocket to the downcomer. The bottom surface of air pocket periodically moved up and down by fluctuation of liquid level in the top section. When the bottom surface of the air pocket was lowest, surface aeration took place. The surface aeration seemed to increase with increasing the circulation liquid velocity in the downcomer. As the initial entrainment of gas bubbles into the top horizontal connection and the gas-liquid separation ability of the connection increased, the size

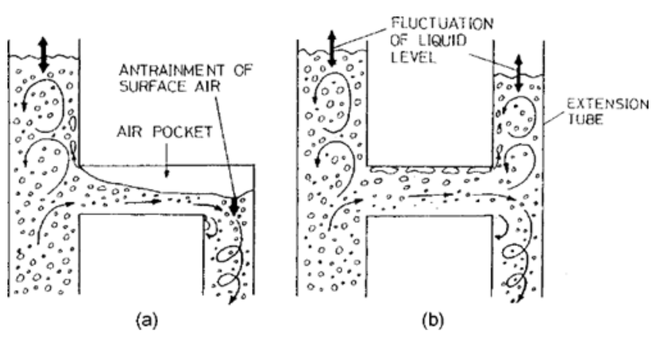

Fig. 2. Configurations of the head region: (a) without the extension tube; (b) with the extension tube.

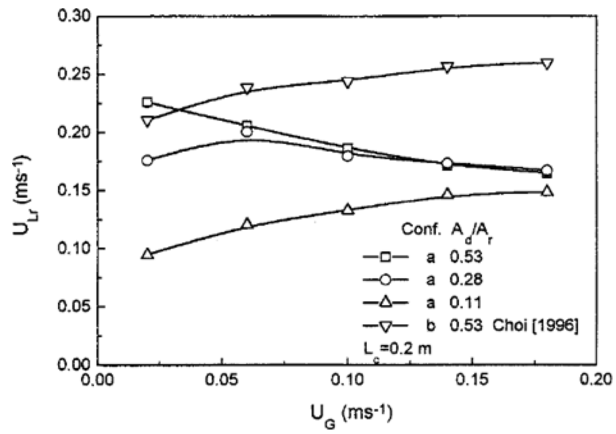

Fig. 3. Effect of the superficial gas velocity on the riser circulation liquid velocity as a function of A_d/A_r.

of the air pocket increased.

The effect of the superficial gas velocity on the circulation liquid velocity in the riser as a function of A_d/A_r is shown in Fig. 3. In airlift reactors, the driving force for liquid circulation is the density difference between the dispersion phases in the riser and the downcomer. In general, the driving force for liquid circulation increased with increasing the superficial gas velocity because of an increase in the density difference. In configuration (a), both the initial entrainment of gas bubbles into the top horizontal connection and the size of air pocket in the connection increased with increasing the superficial gas velocity. An increase in the size of air pocket reduced the circulation liquid velocity due to a decrease in the free cross-section area for the fluid flow in the top horizontal connection. When the minimum value of the free cross-section area was smaller than the cross-section area of the downcomer, the frictional loss of the driving force due to the air pocket in the top horizontal connection became important because the downcomer has the smallest value of cross-section area in external-loop in this study. For A_d/A_r=0.53, the circulation liquid velocity decreased with increasing U_G because the minimum value of the free cross-section area was always smaller than the cross-section area of the downcomer. This result is in agreement with observations made by Mercer [1981]. Bentifraouine et al. [1997a, b] also reported that beyond a critical value of the superficial gas velocity which generated a dispersion height above the top horizontal connection, the circulation liquid velocity decreased with increasing U_G. In this study, the dispersion height was always kept above the top horizontal connection. However, in the case of A_d/A_r=0.28, the maximum value of the circulation liquid velocity was observed because the minimum value of the free cross-section area became smaller than the cross-section area of the downcomer when U_G was larger than a certain value (about 0.06 ms^{-1}). In the case of A_d/A_r=0.11, the circulation liquid velocity continuously increased with increasing U_G because the minimum value of the free cross-section area was always larger than the cross-section area of the downcomer. Snape et al. [1995] observed a similar dependence of U_{Lr} on U_G in an external-loop airlift reactor with configuration (a). In conclusion, three different changes U_{Lr} of with U_G were observed in configuration (a).

On the other hand, the riser circulation liquid velocity increased with increasing A_d/A_r due to decreasing the resistance of liquid cir-

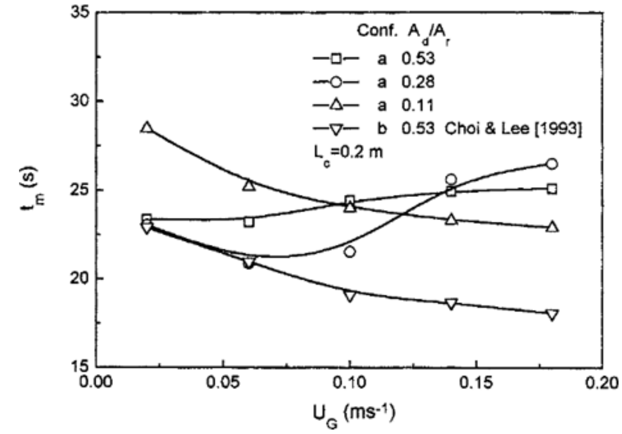

Fig. 4. Effect of the superficial gas velocity on the mixing time as a function of A_d/A_r.

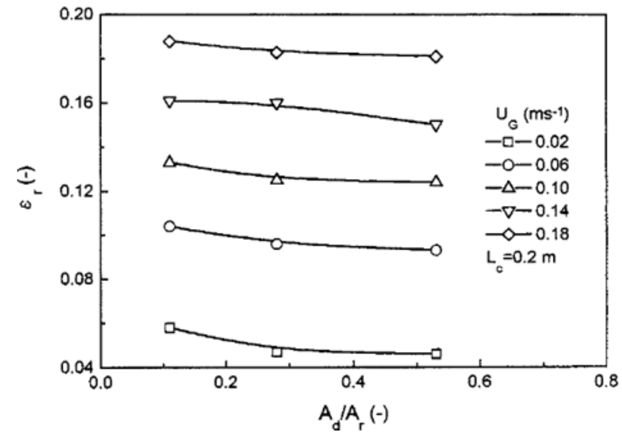

Fig. 6. Effect of A_d/A_r on the riser gas holdup.

culation path [Bello et al., 1984; Popović and Robinson, 1988; Choi and Lee, 1993; Gavrilescu and Tudose, 1997]. The data reported by Choi [1996] are also presented in Fig. 3. For otherwise identical conditions, the riser circulation liquid velocity in the external-loop airlift reactor without an extension tube above the downcomer [configuration (a)] was slower than that in the external-loop airlift reactor with an extension tube above the downcomer [configuration (b)]. This result is in agreement with observations made by Bentifraouine et al. [1997a]. In configuration (b), a large air pocket in the top horizontal connection was not formed, hence the riser circulation liquid velocity increased with increasing U_G.

The effect of the superficial gas velocity on the mixing time as a function of A_d/A_r is shown in Fig. 4. Mixing in airlift reactors has two contributing components: (i) backmixing due to recirculation and (ii) axial dispersion due to turbulence and differential velocities of the gas and liquid phases. It is certain that backmixing was enhanced with increasing the circulation liquid velocity. Therefore, the variation of the mixing time with the superficial gas velocity was the inverse of the variation of the circulation liquid velocity. For otherwise identical conditions, the mixing time for configuration (a) was longer than that for configuration (b). The result means that configuration (b) was a more effective mixer than configuration (a).

Fig. 5 shows the effect of the superficial gas velocity on the riser gas holdup (ε_r) as a function of A_d/A_r. In spite of the change of the riser circulation liquid velocity, the riser gas holdup increased with increasing the superficial gas velocity because the bubble density in the riser increased. The gas holdup data obtained by Choi and Lee [1993] are also presented in Fig. 5. For otherwise identical conditions, the riser gas holdup in configuration (a) was larger than that in configuration (b). On the other hand, the riser liquid circulation velocity increased with increasing A_d/A_r due to decreasing the resistance of liquid circulation path (Fig. 3). For an identical gas velocity, residence time of bubbles in the riser decreased with an increase in the riser liquid circulation velocity. Therefore, as shown in Fig. 6, the riser gas holdup decreased slightly with increasing A_d/A_r. Similar results have been obtained by many investigators in configuration (b) [Bello et al., 1984, 1985a, b; Popović and Robinson, 1987; Choi and Lee, 1993; Choi, 1997].

The effect of the superficial gas velocity on the downcomer gas holdup (ε_d) as a function of the downcomer-to-riser cross-sectional area ratio is shown in Fig. 7. In external-loop airlift reactors, bubbles can be entrained into the top horizontal connection when the circulation liquid velocity is larger than the rising velocities of the bubbles. Large bubbles are separated while they stay at the top horizontal connection. Only small bubbles can be entrained into the downcomer. At the lower superficial gas velocities, the downcomer

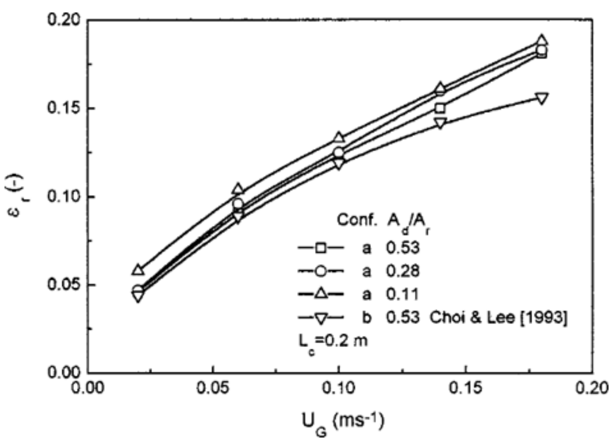

Fig. 5. Effect of the superficial gas velocity on the riser gas holdup as a function of A_d/A_r.

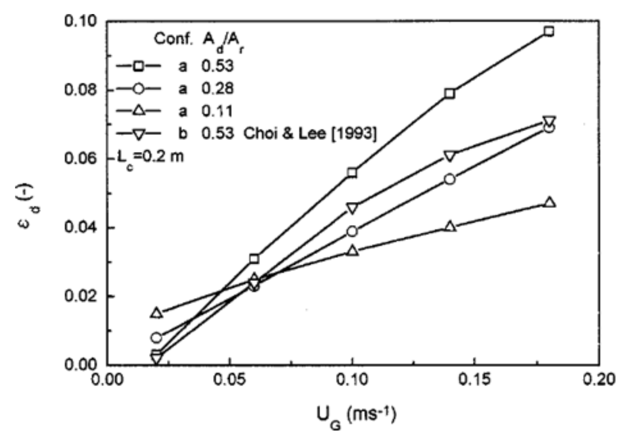

Fig. 7. Effect of the superficial gas velocity on the downcomer gas holdup as a function of A_d/A_r.

gas holdup was mainly caused by the surface aeration from the air pocket because most bubbles, which were entrained into the top horizontal connection, were separated in the connection. Therefore, the downcomer gas holdup decreased with increasing A_d/A_r. However, for the higher superficial gas velocities, the downcomer gas holdup increased with increasing A_d/A_r because the downcomer gas holdup was mainly determined by the amount of the entrained bubbles into the downcomer after passing the top horizontal connection. As the horizontal connection length was increased, the change of dependence of ε_d on A_d/A_r took place at the higher superficial gas velocities. For otherwise identical conditions, the downcomer gas holdup in configuration (a) was larger than that in configuration (b).

Choi et al. [1990], Choi and Lee [1993] and Choi [1997] reported that the horizontal connection length was one of the important design variables for the external-loop airlift reactors with configuration (a). They observed that the horizontal connection length strongly affected the hydrodynamic and the mass transfer performance of the reactors. Figs. 8 and 9 illustrate the effects of the horizontal connection length on the circulation liquid velocity in the riser and the mixing time as a function of A_d/A_r, respectively. As the horizontal connection length increased, both the driving force for fluid circulation and the circulation liquid velocity in the riser increased due to an increase in the gas-liquid separation ability of the top horizontal connection, hence the gas holdups in the riser and downcomer decreased (Figs. 10 and 11). In spite of increasing the circulation liquid velocity, the mixing time increased with increasing

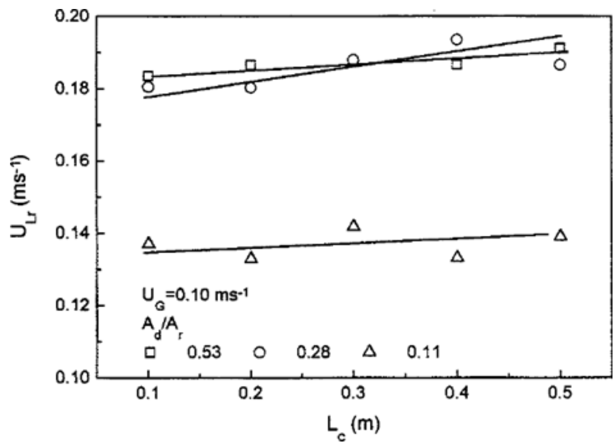

Fig. 10. Effect of the horizontal connection length on the riser gas holdup as a function of A_d/A_r.

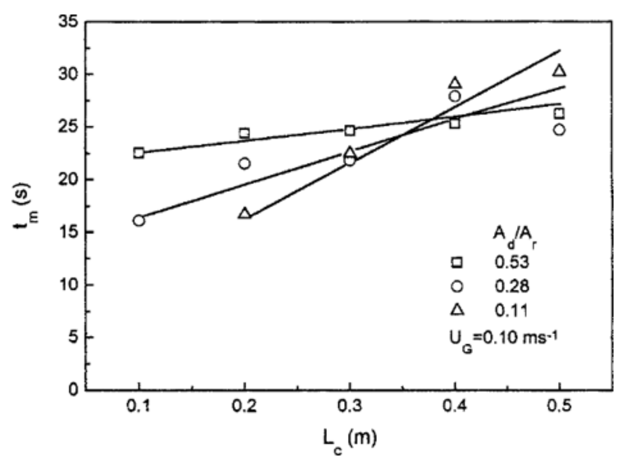

Fig. 8. Effect of the horizontal connection length on the riser circulation liquid velocity as a function of A_d/A_r.

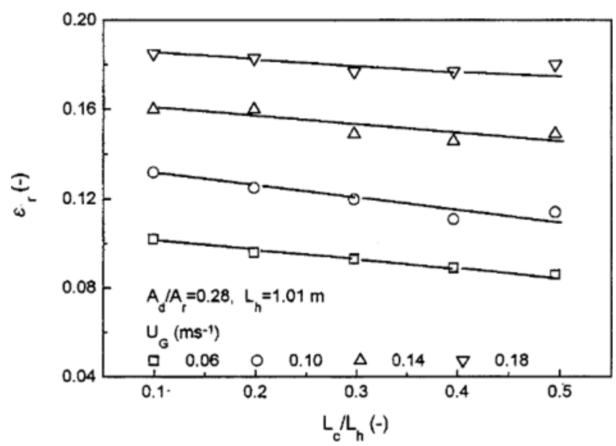

Fig. 11. Effect of the horizontal connection length on the downcomer gas holdup as a function of A_d/A_r.

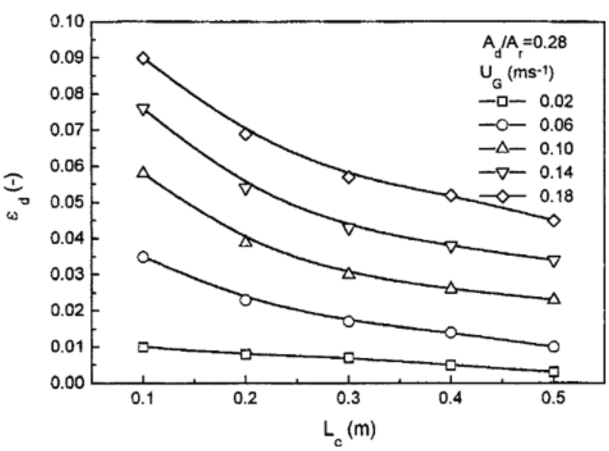

Fig. 9. Effect of the horizontal connection length on the mixing time as a function of A_d/A_r.

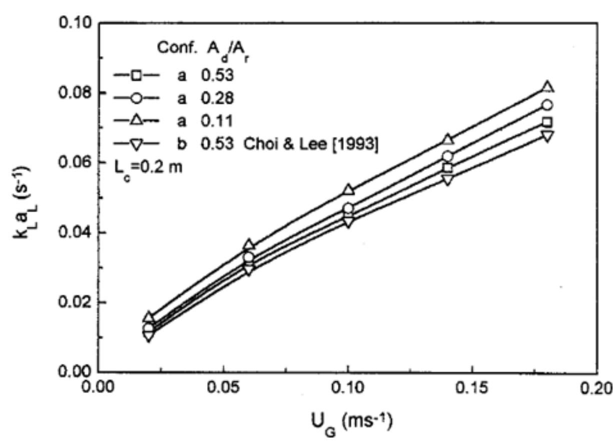

Fig. 12. Effect of the superficial gas velocity on the overall volumetric mass transfer coefficient as a function of A_d/A_r.

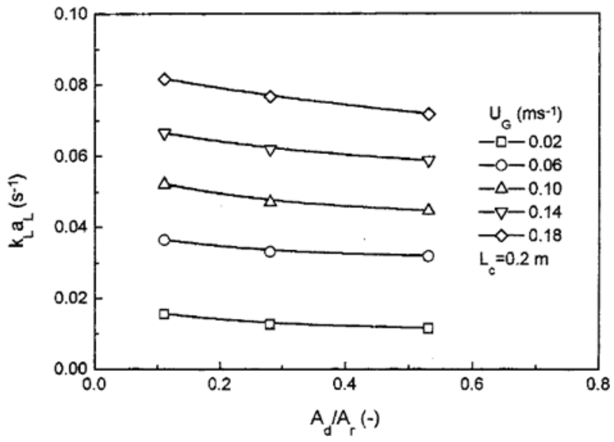

Fig. 13. Dependence of the overall volumetric mass transfer coefficient on A_d/A_r.

the horizontal connection length due to an increase in working liquid volume (Fig. 9).

The overall volumetric oxygen mass transfer coefficient increased as the superficial gas velocity increased as shown in Fig. 12. Fig. 13 shows that a small effect of A_d/A_r on k_La_L at a constant superficial gas velocity was observed. In both the configurations of airlift reactors, there is a consistent pattern of variation of k_La_L with changing A_d/A_r. The downcomer volume increased relative to that of the riser as A_d/A_r increased. Negligible mass transfer in the downcomer has been reported by previous investigators [Bello et al., 1985a; McManamey and Wase, 1986]. In addition, the riser gas holdup decreased due to an increase in the riser circulation liquid velocity as A_d/A_r increased (Fig. 3). Therefore, an increase in A_d/A_r decreased k_La_L. The similar trend has been previously observed by Bello et al. [1985a] and Choi and Lee [1993] in configuration (b). In Fig. 12, the data obtained by Choi and Lee [1993] in configuration (b) are also presented. The k_La_L values obtained in configuration (a) were higher than the corresponding values obtained in configuration (b) because the riser gas holdup in configuration (a) was higher than that in configuration (b) and mass transfer in the downcomer was negligibly small.

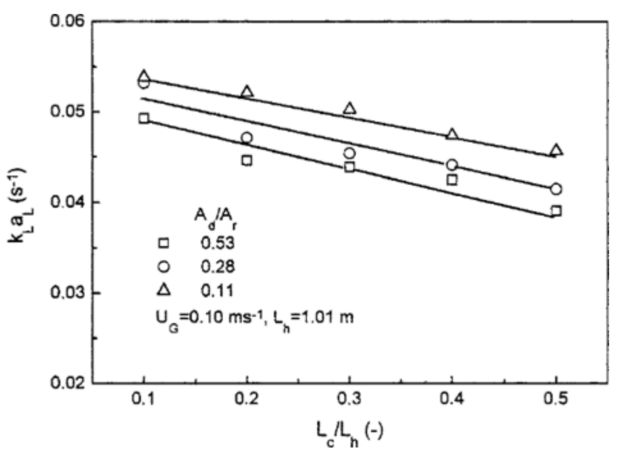

Fig. 14. Effect of the horizontal connection length on the overall volumetric mass transfer coefficient as a function of A_d/A_r

The effect of the horizontal connection length on k_La_L is shown in Fig. 14. An increase in the horizontal connection length resulted in an increase of working liquid volume. In addition, due to an increase in the circulation liquid velocity, the riser gas holdup decreased with increasing L_c. Therefore, k_La_L decreased as the horizontal connection length increased.

In order to achieve meaningful correlations of the experimental results obtained in the airlift reactors, the main parameters which influence the results in the reactors must be taken into account. In this study, the superficial gas velocity, the downcomer-to-riser cross-sectional area ratio and the horizontal connection length are considered. Liquid phase physiochemical properties and other geometric parameters have not been studied in this work and hence are not considered. A close fit was obtained by using exponential multiple regression on the experimental data.

The riser gas holdup results obtained in the airlift reactors without the extension tube were well represented by Eq. (4) with a correlation coefficient of 0.995.

$$\varepsilon_r = 0.431\, U_G^{0.580} \left(\frac{A_d}{A_r}\right)^{-0.040} \left(\frac{L_c}{L_h}\right)^{-0.042} \tag{3}$$

As can be seen from the correlation, ε_r is essentially directly proportional to $U_G^{0.580}$, with A_d/A_r having a small effect and dimensionless connection length (L_c/L_h) also having a small effect. The experimental data of k_La_L were well fitted by Eq. (4) with a correlation coefficient of 0.998.

$$k_La_L = 0.231\, U_G^{0.821} \left(\frac{A_d}{A_r}\right)^{-0.080} \left(\frac{L_c}{L_h}\right)^{-0.127} \tag{4}$$

The correlations can be used for design calculations and the constants in the correlations depend on physical properties of liquid, flow regimes, sparger design, and geometry of the reactor.

CONCLUSIONS

The riser circulation liquid velocity in configuration (a) was slower than that in configuration (b). The riser and downcomer gas holdups, the mixing time and the overall volumetric mass transfer coefficient in configuration (a) were larger than those in configuration (b), respectively. Configuration (a) was a more ineffective mixer than configuration (b), but configuration (a) showed higher mass transfer performance than configuration (b).

The riser and downcomer gas holdups and the overall volumetric mass transfer coefficient were found to decrease with increasing the horizontal connection length. As the superficial gas velocity increased, the riser and downcomer gas holdups and the overall volumetric mass transfer coefficient continuously increased, whereas both the circulation liquid velocity and the mixing time showed various changes according to A_d/A_r values. The riser gas holdup and the overall volumetric mass transfer coefficient decreased slightly with increasing A_d/A_r. Useful correlations for the riser gas holdup and the overall volumetric mass transfer coefficient were obtained in the airlift reactors.

NOMENCLATURE

A_d : cross-sectional area of downcomer [m^2]

A_r : cross-sectional area of riser [m^2]
i.d. : inside diameter [m]
k_La_L : overall volumetric mass transfer coefficient based on liquid volume [s^{-1}]
L_c : horizontal connection length [m]
L_h : height between horizontal connections [m]
t_c : circulation time [s]
t_m : mixing time [s]
U_G : superficial gas velocity based on riser cross-sectional area [ms^{-1}]
U_{Lr} : superficial circulation liquid velocity in riser [ms^{-1}]
V_{EL} : effective circulating liquid volume [m^3]
V_L : total liquid volume in reactor [m^3]
V_t : volume of top section [m^3]

Greek Letters
ε_d : downcomer gas holdup
ε_r : riser gas holdup
ε_t : gas holdup in top section

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