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CIRCULATION LIQUID VELOCITY IN EXTERNAL-LOOP AIRLIFT REACTORS

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Abstract – In the tracer impulse method using only a conductivity probe, the more recommendable calculation method for the circulation liquid velocity was suggested, which decreased the errors resulted from the response time. The effects of the horizontal connection length ($0.1 \leq L_c \leq 0.5$ m), the cross-sectional area ratio of downcomer-to-riser ($0.11 \leq A_d/A_r \leq 0.53$), and the superficial gas velocity ($0.02 \leq U_G \leq 0.18$ m s^{-1}) on the circulation liquid velocity were studied. The horizontal connection length as well as U_G and A_d/A_r had a significant effect on the circulation liquid velocity. The circulation liquid velocity increased with increasing L_c.

Key words: Circulation Liquid Velocity, Airlift Reactor, Tracer Impulse Method, Conductivity Probe

INTRODUCTION

Circulation liquid velocity is one of the most relevant parameters for proper design and operation of airlift reactors. Circulation liquid velocity can be measured by either the direct or indirect measurement methods. For the direct measurement of the circulation liquid velocity, a flow meter [Chakravarty et al., 1974; Merchuk and Stein, 1981; Herskowitz and Merchuk, 1986; Merchuk, 1986; Siegel et al., 1986; Verlaan et al., 1986; Popovic and Robinson, 1987, 1988] or a constant-temperature anemometer [Lippert et al., 1983] is usually used. If the flow meter is used during cell cultivation, there may be some problems with respect to maintenance and calibration of the meter. In addition, the meter can affect the circulating gas-liquid flow in the reactor. The constant-temperature anemometer has some difficulties in treatment of probe signals. The electrical signal obtained by the probe has to be linearized, digitized, and preprocessed by a computer. However, the direct determination of the circulation liquid velocity by a constant-temperature anemometer seems to be especially adequate for biological systems because the method does not make any serious condition.

In contrast to the direct measurement methods, the indirect measurement methods, such as the tracer impulse method [Bello, 1981, 1984; Weiland, 1984; Chisti et al., 1988, 1995; Chisti and Moo-Young, 1991; Jose and Merchuk, 1991; Wachi et al., 1991; Choi and Lee, 1993; Livingston and Zang, 1993; Shamlou et al., 1994; Li et al., 1995; Lu et al., 1995] and the flow follower technique [Mercer, 1981; Fan et al., 1984; Fields et al., 1984; Jones, 1985; Hiyahara et al., 1986; Kemblowski, 1993; Choi et al., 1995], are relatively simple. Therefore, many researchers have chosen the indirect methods for determination of the circulation liquid velocity. However, the flow follower technique can not be used when the reactor is opaque. In the tracer impulse method, hot solution, acid, base, and salt solution are used as a tracer.

When the two pH or conductivity probes which had almost same value of the response time were used for the tracer impulse method, the linear liquid velocity could be easily calculated from the time difference between the responses of the probes and the vertical distance between the probes [Bello, 1981; Chisti et al., 1988, 1995; Jose and Merchuk, 1991; Wachi et al., 1991; Lu et al., 1995]. On the contrary, when one can use only a pH probe or a conductivity probe for the tracer impulse method, it is important to choose the calculation method in order to exactly calculate the circulation liquid velocity. Previous researchers [Weiland, 1984; Chisti and Moo-Young, 1991] determined the mean liquid velocity from the length of the mean liquid path and the circulation time:

$$U_{Lm} = \frac{X_c}{t_c} \tag{1}$$

where X_c is the length of the mean liquid path and t_c is the circulation time. However, they did not represent how to determine the length of the mean liquid path in their papers. It is certain that the circulation path length can be calculated from the effective circulating liquid volume in the reactor and the dimensions of the reactor as follows:

$$X_c = \frac{V_{EL}}{A_m} \tag{2}$$

Therefore, how to reasonably define the effective circulating liquid volume in the reactor still remains a problem when the circulation liquid velocity is determined by the calculation method.

In our previous experiments [Choi and Lee, 1993], the linear liquid velocity in the downcomer was directly determined as the dividing the distance between the injection point and the conductivity probe, L, by the time for the first peak to appear, t_1, as follows:

$$V_{Ld} = \frac{L}{t_1} \tag{3}$$

Eq. (3) is exact when there is no effect of the response time of the probe on the trace response curve. Since the response time was not completely considered in the calculation procedure, it is certain that the previous data for the circulation liquid velocity had large deviations with the true values.

In this paper, the more recommendable calculation method for the circulation liquid velocity which decreased the errors resulted from the response time was suggested. The effects of the horizontal connection length, the cross-sectional area ratio of downcomer-to-riser, and the superficial gas velocity on the circulation liquid velocity were investigated.

EXPERIMENTAL

Fig. 1 shows a schematic diagram of the external-loop airlift reactors used in this work. The airlift vessel was made of acrylic transparent pipe with 6 mm thickness. The horizontal connection length was changed by the exchange of the connection section. The cross-sectional area ratio of downcomer-to-riser was varied by the reciprocation of the interchangeable downcomer. The riser was a column with internal diameter of 0.149 m. The interchangeable downcomers were three pipes with internal diameters of 0.108, 0.079, and 0.049 m. The circulation loop except the exchangeable downcomer was made of a pipe with internal diameter of 0.108 m. Tap water and air were used as the liquid and gas phases in the experiments. All experiments were carried out at room temperature and atmospheric pressure.

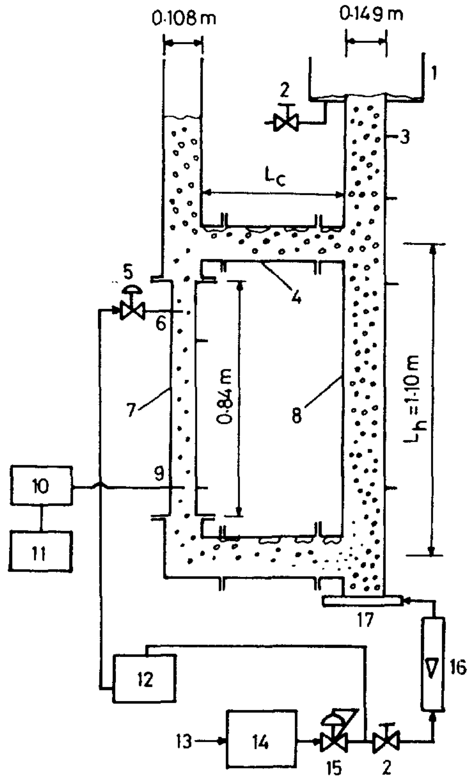

Fig. 1. Schematic diagram of experimental apparatus.

(1) Wear box	(10) Conductivity meter
(2) Valve	(11) Recorder
(3) Pressure tap	(12) Salt solution tank
(4) Interchangeable connection	(13) Air line
(5) Solenoid valve	(14) Air filter
(6) Injection tube	(15) Pressure regulator
(7) Interchangeable downcomer	(16) Rotameter
(8) Riser	(17) Gas sparger
(9) Conductivity probe	

For measurement of the liquid velocity, 10 ml of 4M potassium chloride solution was used as a tracer. The tracer was injected at a point in the downcomer, 1.00 m from the gas sparger, during 0.5 s. The response of a pulse input of the tracer was measured by a conductivity probe which was installed at the hight of 0.40 m from the sparger in the downcomer. At the moment of trace injection a chart recorder was switched on which was used to monitor the conductivity in the reactor. A typical tracer curve is shown in Fig. 2. The overall gas holdup was determined by comparison of the aerated and unaerated liquid heights. The gas holdups in the riser, the downcomer and the top section above the riser were measured by manometric method.

A conductivity probe has a response time. In addition, the response time depends on the changing magnitude of the conductivity of the sample. Because the effect of the response time on the circulation time can be negligible, the following calculation method using the circulation time is more recommendable to decrease the errors resulted from the response time. For the external-loop airlift reactors used in this work, the effective circulating fluid volume can be defined as the volume enclosed by connecting the internal surfaces of the channels such as the riser, the top and bottom connection sections and the downcomer. The circulation time is the summation of the residence times in the individual sections.

$$t_c = t_r + t_{tc} + t_d + t_{bc} \tag{4}$$

$$t_c = \frac{L_h + D_c}{V_{Lr}} + \frac{L_c}{V_{Ltc}} + \frac{L_{id}A_d + (L_h - L_{id} + D_c)A_c}{V_{Ld}A_d} + \frac{L_c}{V_{Lbc}} \tag{5}$$

The continuity criterion leads to the following relationship between the liquid velocities in the individual sections.

$$U_{Lr}A_r = U_{Ld}A_d = U_{Ltc}A_c = U_{Lbc}A_c \tag{6}$$

The linear velocity and the superficial velocity are related as follows:

$$V_{Lr} = \frac{U_{Lr}}{1 - E_r} \tag{7}$$

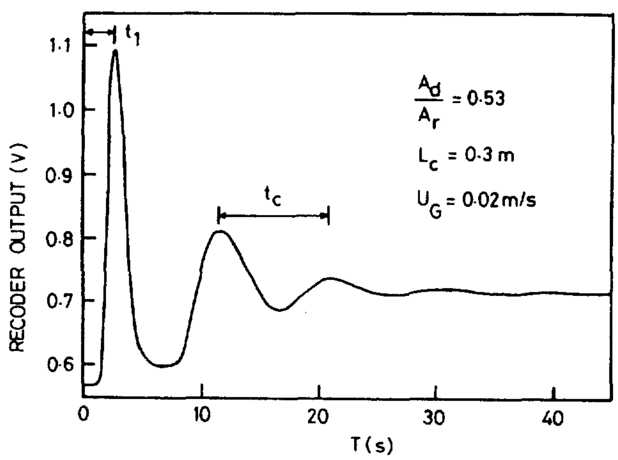

Fig. 2. Typical trace curve.

$$V_{Ld}=\frac{U_{Ld}}{1-E_d} \tag{8}$$

$$V_{Ltc}=\frac{U_{Ltc}}{1-E_{tc}} \tag{9}$$

and

$$V_{Lbc}=\frac{U_{Lbc}}{1-E_{bc}} \tag{10}$$

Substitution Eqs. from (6) to (10) to Eq. (5) and rearrangement give

$$U_{Lr}=\frac{1}{A_r t_c}\{(L_h+D_c)(1-E_r)A_r+L_c(1-E_{tc})A_c + [L_{td}A_d+(L_h-L_{td}+D_c)A_c](1-E_d)+L_c(1-E_{bc})A_c\} \tag{11}$$

It is vary hard to directly measure the gas holdups in the top and bottom connections. Based on the assumptions that $E_{tc}=E_{td}$ and $E_{bc}=E_d$, the gas holdup in the top connection can be determined from the overall gas holdup and the other individual gas holdups using the following equation:

$$V_o E_o=V_r E_r+V_d E_d+V_{tr}E_{tr}+V_{td}E_{td}+V_{tc}E_{tc}+V_{bc}E_{bc} \tag{12}$$

Then the riser circulation liquid velocity can be calculated by Eq. (11) using the circulation time, the data for the individual gas holdups, and the reactor's dimensions.

RESULTS AND DISCUSSION

The effect of the superficial gas velocity, U_G, on the riser superficial liquid velocity, U_{Lr}, as a function of the cross-sectional area ratio of downcomer-to-riser is shown in Fig. 3. The riser superficial liquid velocity was increased with increasing U_G. As U_{Lr} was increased, more bubbles were entrained into the downcomer and then the downcomer gas holdup increased with almost constant rate [Choi and Lee, 1993]. On the other hand, as U_G was increased, the increased rate of the riser gas holdup with increasing U_G was gradually decreased because the flow pattern in the riser changed from bubble to churn-turbulent flow. Choi and Lee [1993] reported that log-log plots of the riser gas holdups with U_G showed a straight line and the slope of the line changed at the point of flow transition from bubble to churn-turbulent flow ($U_G \simeq 0.06$ m s^{-1}). Therefore, the increased rate of U_{Lr} with increasing U_G also gradually reduced. As A_d/A_r was increased, the liquid circulation velocity reduced due to an increase in the resistance of the liquid circulation path. Similar trend has been obtained by previous investigators [Bell et al., 1984; Siegel et al., 1986; Popovic and Robinson, 1987]. The data for our previous works [Choi and Lee, 1993] are also shown in Fig. 3. Since the response time was not entirely considered in the previous works, the previous data for the circulation liquid velocity were underestimated as shown in Fig. 3. The data calculated by the present calculation method were about 2-fold higher than the previous data because the present method led to a decrease in the errors resulted from the response time.

The horizontal connection length had a significant effect on U_{Lr}. An increase in horizontal connection length has two opposing factors. One of them is an increase in gas-liquid separation efficiency of the top connection due to increasing its volume, which increases the driving force for liquid circulation. The other is an increase in frictional losses of the driving force for liquid circulation. It is certain that the top connection roles a gas-liquid separator because the liquid-phase flow in the section flows horizontally. Gas bubbles are separated from the two-phase flow due to the buoyancy force during the flow passes the region. Because the former was greater than the latter, the circulation liquid velocity increased with increasing L_c as shown in Fig. 4. In conclusion, although the calculation method for the circulation liquid velocity was changed, the effects of the horizontal connection length, the superficial gas velocity, and the cross-sectional area ratio of downcomer-to-riser on the circulation liquid velocity did not vary.

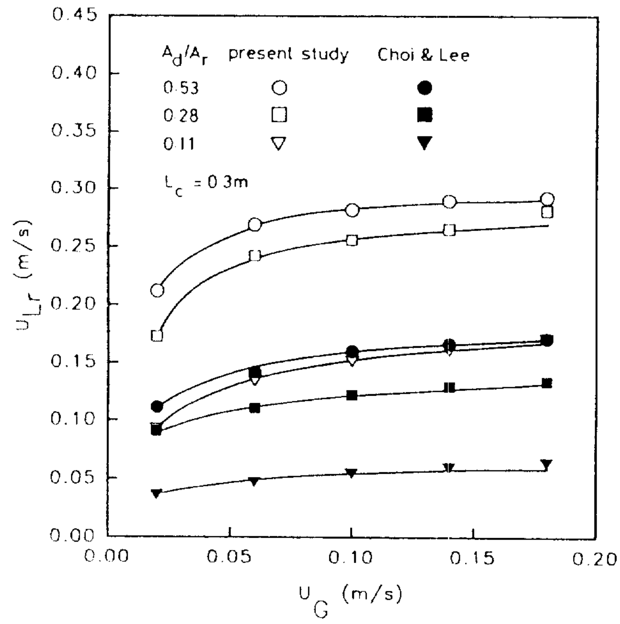

Fig. 3. Effect of superficial gas velocity on riser superficial liquid velocity as a function of cross-sectional area ratio of downcomer-to-riser.

Correlating 75 experimental points for the external loop airlift reactors, the following equation has been obtained, with the regression coefficient of 0.943:

$$V_{Lr}=0.795\,U_G^{0.233}\left(\frac{A_d}{A_r}\right)^{0.330}\left(\frac{L_c}{L_h}\right)^{0.137} \tag{13}$$

Bello [1981] theoretically derived a dependence of the riser linear velocity on the cube root of the riser superficial gas velocity. On the other hand, the proportionality between V_{Lr} and $U_G^{0.40}$ has been reported by Merchuk [1986]. The dependence of V_{Lr} on A_d/A_r also differs from that observed by Bello et al. [1984]. It can be explained by that the constants in the correlations depend on the physical properties of the liquid, the flow regime, the sparger design, and geometry of the reactor. Comparison of experimental to calculated data is shown in Fig. 5. In Fig. 5 one can see a good agreement of calculated and experimental data. On the basis of Eq. (13) the circulation liquid velocity

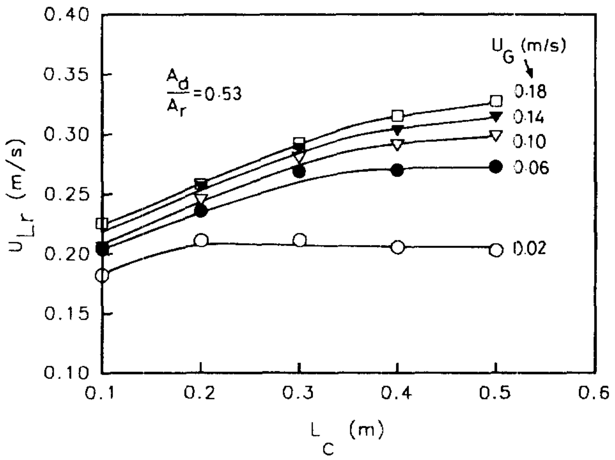

Fig. 4. Effect of horizontal connection length on riser superficial liquid velocity.

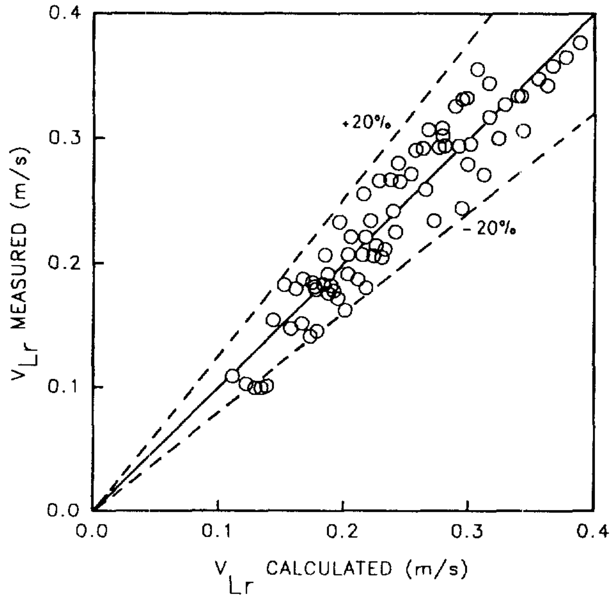

Fig. 5. Comparison of V_{Lr} data using Eq. (13).

can be successfully predicted using gas velocity and construction characteristics of the reactor only.

CONCLUSION

The effects of the horizontal connection length ($0.1 \leq L_c \leq 0.5$ m), the cross-sectional area ratio of downcomer-to-riser ($0.11 \leq A_d/A_r \leq 0.53$), and the superficial gas velocity ($0.02 \leq U_G \leq 0.18$ m s^{-1}) on the circulation liquid velocity were studied in external-loop airlift reactors. The circulation liquid velocity was measured by the tracer impulse method using only a conductivity probe. In the case, the calculation method of the circulation liquid velocity using the circulation time was more recommendable, which decreased the errors resulted from the response time. The horizontal connection length as well as U_G and A_d/A_r had a significant effect on the circulation liquid velocity. The circulation liquid velocity increased with increasing L_c. An useful correlation for the circulation liquid velocity as parameters of U_G, A_d/A_r, and L_c was obtained.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A : cross-sectional area [m^2]
D : diameter [m]
E : gas holdup [-]
L : distance between the injection point and the probe [m]
L_c : horizontal connection length [m]
L_h : hight between horizontal connections [m]
T : time [s]
t : resident time [s]
t_c : circulation time [s]
t_1 : time for the first peak to appear [s]
U_G : superficial gas velocity [m s^{-1}]
U_L : superficial liquid velocity [m s^{-1}]
V : volume [m^3]
V_L : linear liquid velocity [m s^{-1}]
V_{EL} : effective circulating liquid volume [m^3]
X_c : circulation path length [m]

Subscripts

bc : bottom connection
c : connection
d : downcomer
id : interchangeable downcomer
m : mean
o : overall
r : riser
tr : top section over the riser
td : top section over the downcomer
tc : top connection

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