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Bubble circulation regimes in a multi-stage internal-loop airlift reactor

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ABSTRACT

Specially designed internals were used in a novel multi-stage internal-loop airlift slurry reactor to decrease liquid backmixing and provide for a homogeneous suspension of solid particles. There was three bubble circulation regimes with different bubbling characteristics in the downcomer of the bottom stage: bubble-free regime (BFR), transition regime (TR) and complete bubble circulation regime (CBCR). The effects of the unaerated liquid level and superficial gas velocity on the bubble circulation regimes were investigated. The unaerated liquid level significantly affected the regime transition from the TR to CBCR, but had a negligible effect on the transition from the BFR to TR. The axial profile of the gas holdup in the downcomer was non-uniform in the BFR, but almost uniform in the CBCR. With increasing superficial gas velocity, the liquid circulation velocity increased in the BFR, remained approximately constant in the TR, and then increased in the CBCR. A mechanism for the regime transitions that was based on the measured gas holdup, liquid circulation velocity and bubble penetration depth was given.

1. Introduction

Bubble columns and airlift loop reactors are widely used in chemical and biochemical processes [1–4]. Their advantages over the continuous stirred tank reactor (CSTR) include simple construction, good heat transfer and easier scale-up. However, the single-stage bubble column or airlift reactor has the disadvantage of intense liquid backmixing, thus, it will be very inefficient for a process that requires a high conversion of the liquid reactants. In our previous work [5], a novel multi-stage internal-loop airlift reactor to decrease the backmixing of the liquid phase, by analogy with the tanks-in-series concept, was proposed. The schematics of a two-stage internal-loop airlift reactor are shown in Fig. 1. By using a specially designed inter-stage internal with a smaller opening ratio and separate flowing channels for the gas and liquid–solid phases, this multi-stage reactor had less inter-stage liquid backmixing [5] than the multi-stage bubble column [6,7] or the multi-stage external-loop airlift reactor [8] reported in the literature. In addition, it also achieved a uniform distribution of the solid particles, which was not studied in other multi-stage reactors in the literature. The good performance of the multi-stage reactor in our works is closely linked to the liquid circulation in each stage and special structure of the internal.

However, with such inter-stage internals, a gas layer formed below the internal, which affected the liquid level and liquid circulation in the bottom stage, as shown in Fig. 2. When the liquid level was higher than the upper edge of the draft tube, there is liquid circulation between the riser and downcomer. The liquid circulation is important to suspend the solid particles homogeneously at a relatively low superficial gas velocity for a slurry system. When the liquid level was lower than the upper edge of the draft tube, the liquid circulation cannot be formed.

In the published works on an internal-loop airlift reactor without a gas–liquid separator, there are different regimes of bubble swarm in the downcomer according to the bubble circulation in the riser and downcomer [9–12]. Siegel et al. [9] described two main flow regimes, namely, the straight bubble flow and oscillating bubble flow, based on the liquid velocity in the downcomer. Recently, Heijnen et al. [10], van Benthum et al. [11] and Al-Masry [12] described three regimes, which is shown in Fig. 3: at low superficial gas velocities, the flow is in the bubble-free regime (BFR) where no bubbles exist in the downcomer; with an increase in the superficial gas velocity, the flow enters the transition regime (TR) where some bubbles are entrained into and partially fill the downcomer; with a further increase in the superficial gas velocity, the flow enters the complete bubble circulation regime (CBCR) where the liquid circulation velocity becomes large enough to entrain gas bubbles in the downcomer back to the riser from below the draft tube. Heijnen et al. [10] mainly investigated the effect of solid particles on the liquid circulation for the CBCR, and did not study the BFR and TR. van Benthum et al. [11] studied the regime transition from the TR to CBCR. Al-Masry [12] only studied the BFR. However, the effects of the liquid level on the regime transition and hydrodynamics in the different regimes have not yet been studied in the

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Nomenclature

A_d	cross-sectional area in the downcomer (m^2)
A_r	cross-sectional area in the riser (m^2)
h	bubbles penetration depth in the downcomer (m)
h_0	vertical distance between two tapping ports in the relevant measurement zone (m)
H	liquid height above the top of the draft tube (m)
H_0	distance between two conductivity probes (m)
H'	height of the draft tube (m)
t	response time difference of the two response curves (s)
U_g	superficial gas velocity (m/s)
U_l	superficial liquid velocity (m/s)
V_lc	liquid circulation velocity (m/s)
V_ld	linear liquid velocity in the downcomer (m/s)
V_lr	linear liquid velocity in the riser (m/s)

Greek letters

ε_g	gas holdup
ρ_l	density of the liquid phase ($\mathrm{kg/m}^3$)

literature. In a multi-stage airlift reactor, the liquid level in each stage is related to the reactor structure parameters, system physical properties and operating conditions, thus its effect must be considered in the design of a multi-stage internal-loop airlift reactor.

This work focused on bubble circulation regimes in a multi-stage internal-loop airlift reactor, but the experiments were carried out in a single-stage internal-loop airlift reactor without a gas–liquid separator because it can present the hydrodynamics of a multi-stage internal-loop airlift reactor except the top stage and the liquid level can be separately controlled in a single-stage reactor. This work studied the effects of the liquid level and superficial gas velocity on the bubble circulation regimes. The liquid circulation velocity, gas holdups in the riser and downcomer and penetration depth of bubbles in the downcomer in each flow regime were investigated. The transition mechanisms were analyzed using the measured gas holdup, liquid circulation velocity and bubble penetration depth. A transition criterion was proposed based on the different changes in the ratio between gas holdups in the downcomer and riser with the superficial gas velocity.

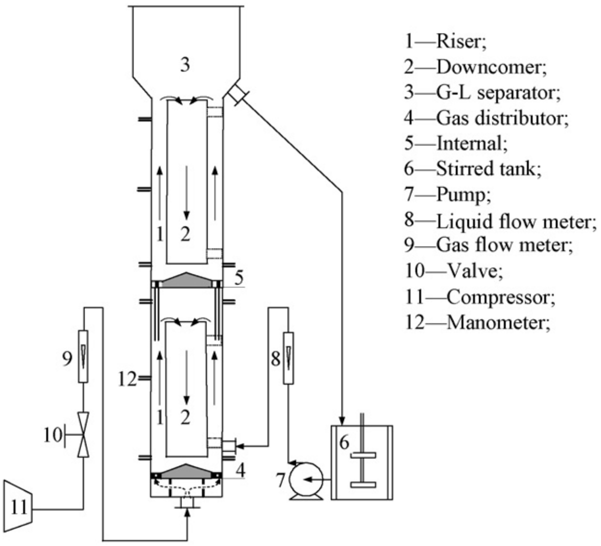


Fig. 1. Schematic of the multi-stage internal-loop airlift reactor.

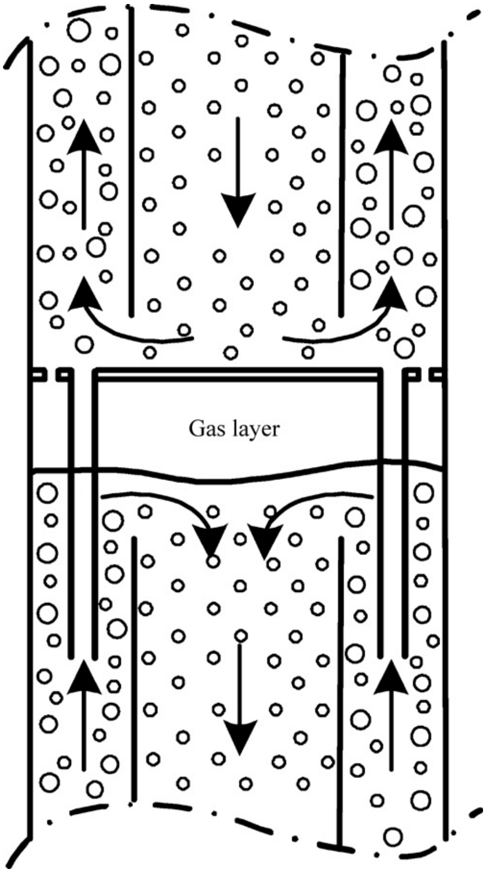


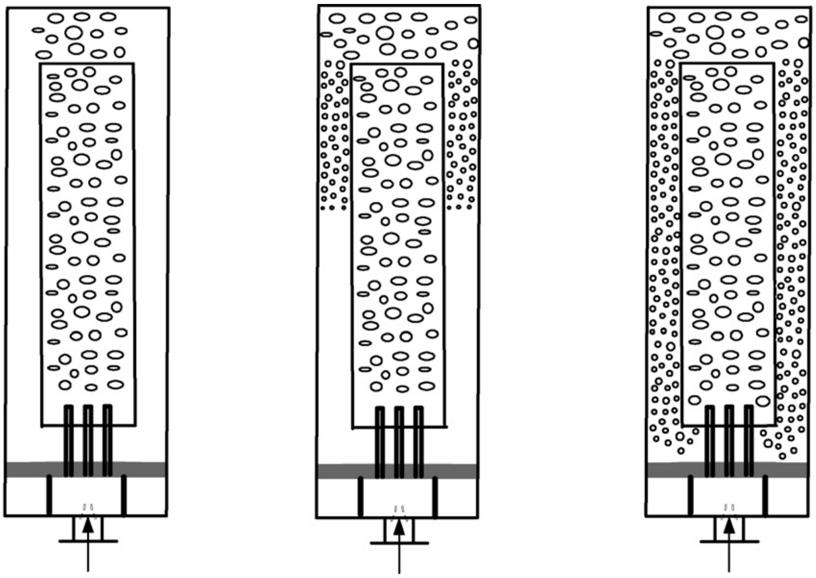
Fig. 2. Flow pattern with liquid circulation when the liquid level is higher than the draft tube.

2. Experimental

2.1. Apparatus

In our previous work, the experimental apparatus was a two-stage airlift reactor with each stage being an annular internal-loop section. The inter-stage internal was a perforated plate with three long tubes, where the gas flowed through the orifices and the liquid–solid slurry flowed through the tubes. With the annular region as the riser and the draft tube as the downcomer, it was difficult to observe and measure the bubble penetration depth in the downcomer. In this work, some modifications were made to the experimental apparatus, as shown in Fig. 4. A gas distributor with orifices in the central region was used, and the reactor was operated in a central internal-loop manner. The single-stage reactor used to present the multi-stage reactor was a vertical Plexiglas column with 0.20-m outer diameter, 0.19-m inner diameter and 1.35-m height. A draft tube of 0.12-m outer diameter, 0.11-m inner diameter and 0.10-m height was installed coaxially inside the column.

Air and tap water were used as the gas and liquid phases, respectively. Air was pumped into the system from the bottom of the reactor and distributed by three tubes perforated with 18 holes of 1.5-mm diameter. The tubes were located in the central region to prevent the gas from entering the annular region. The difference in the gas holdups in the riser and downcomer formed a density difference, which drove the liquid circulation through the riser and downcomer.



Bubble free regime ($V_{lc}<V_{bs}$) Transition regime ($V_{lc}=V_{bs}$) Complete bubble circulation regime ($V_{lc}>V_{bs}$)

Fig. 3. The three bubble circulation regimes in an internal-loop airlift reactor.

2.2. Measuring method

The bubble penetration depth in the downcomer was measured by visual observation. Three parallel measurements were carried out at a given operating condition. The final result was determined as the average value, with an average deviation within ±5%.

The axial profiles of the average gas holdup in the riser and downcomer were measured with the pressure drop method. In the riser, two tapping ports were located 11 and 92 cm above the gas distributor plate. In the downcomer, five different ports were located 11, 30, 51, 71 and 92 cm above the gas distributor plate. In bubble columns and airlift reactors, the friction pressure drop is usually negligible compared with the static pressure drop [13]. Thus, the local static pressure drop (ΔP) between the two tapping ports with vertical space of h_0 is

$$\Delta P = \rho_l g h_0 (1 - \varepsilon_g) \tag{1}$$

where ρ_l is the liquid density and ε_g is the gas holdup. Rearrangement of Eq. (1) leads to

$$\varepsilon_g = 1 - \frac{\Delta P}{\rho_l g h_0} \tag{2}$$

When the pressure drop is measured, the gas holdup can be determined with Eq. (2). Three parallel measurements were carried out in a given operating condition each time. The final result was determined as the average value, with an average deviation within ±3%.

The liquid circulation velocity was measured with two electrical conductivity probes. The probes were modified by covering the tip of the probe with a mesh to prevent gas bubbles from entering the measuring volume. Saturated KCl solution was used as the tracer. After the flow reached steady state, some KCl solution was injected into the system through a port of 5 cm below the top of draft tube. The changes in the electrical conductivity were measured with two probes located 20 and 72 cm below the top of draft tube, respectively. The conductive signals were sampled with an A/D converter at a sampling frequency of 10 Hz and stored in a PC. The liquid circulation velocity in the downcomer was determined by

$$V_{lc} = \frac{H_0}{t} \tag{3}$$

where H_0 is the distance between the two conductivity probes and t is the time difference between the two response curves.

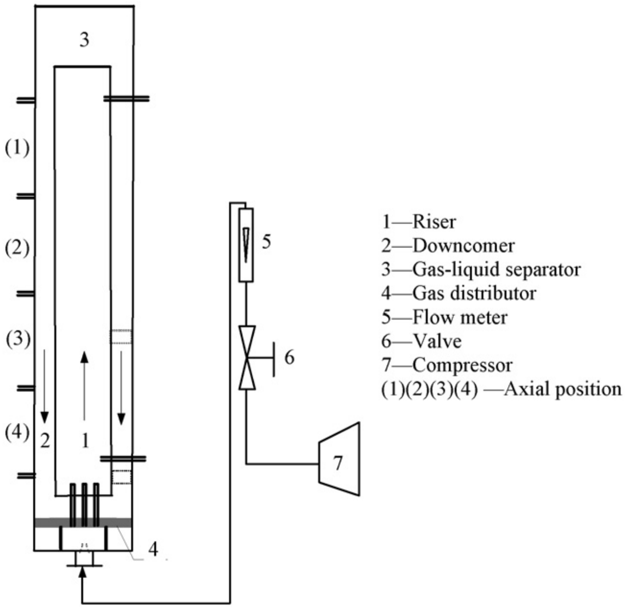


Fig. 4. Schematic of the experimental setup.

3. Results and discussion

3.1. Bubble circulation regimes

Three bubble circulation regimes with different bubbling characteristics in the downcomer were found, namely, a bubble-free regime, transition regime and complete bubble circulation regime.

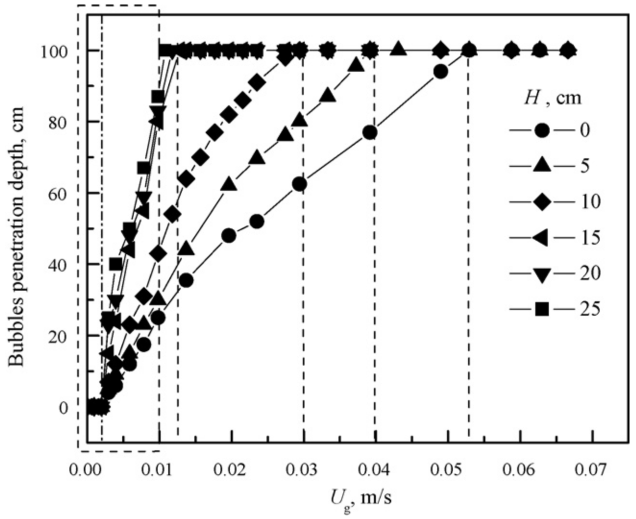


Fig. 5. Effects of the liquid level and superficial gas velocity on the bubble circulation regimes for a wide range of superficial gas velocity.

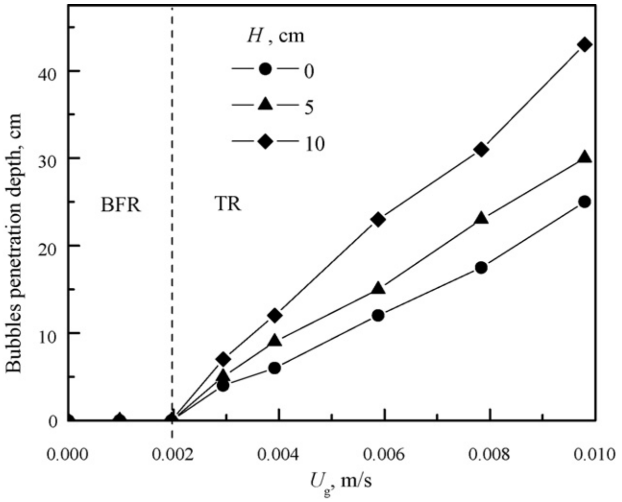


Fig. 6. Effects of the liquid level and superficial gas velocity on the bubble circulation regimes at low superficial gas velocities.

The reason and condition for the existence of three bubble circulation regimes can be analyzed as follows. The BFR existed at low superficial gas velocities where the liquid circulation velocity in the downcomer was less than the average slip velocity of bubble swarm. In the BFR, the gas holdup in the riser increased with increasing superficial gas velocity, and resulted in an increase in the driving force and in the liquid circulation velocity. When the liquid circulation velocity in the downcomer became equal to the average slip velocity of the bubble swarm, the flow entered the TR. In the TR, the axial profile of the gas holdup in the downcomer was non-uniform. The BCCR existed at a higher superficial gas velocity. In this flow regime, the liquid circulation velocity in the downcomer was larger than the average slip velocity of the bubble swarm, and the gas holdup in the downcomer became uniform in the axial direction.

Fig. 5 shows that at an unaerated liquid level of 0 cm, the TR existed for a wide range of superficial gas velocity. Livingston and Zhang [14] reported a similar phenomenon but did not make a detailed discussion. The BFR and TR are not desired in a reactor because of the unsatisfactory contact between the gas and liquid phases that will lead to poor reaction conversion and selectivity. For a given reactor structure and system physical properties, the regime transitions between the BFR, TR and CBCR are mainly determined by the superficial gas velocity and unaerated liquid level. A detailed study of the effects of these parameters is needed for a better understanding of the hydrodynamics, and optimum design and operation of the reactor.

3.2. *Effect of the liquid level on bubble circulation regimes*

The effects of the liquid level and superficial gas velocity on the bubble circulation regimes are shown in Figs. 5 and 6. The results showed that the unaerated liquid level had an insignificant effect on the transition from the BFR to TR, with a transition superficial gas velocity of about 0.002 m/s at all liquid levels. However, the effect of the liquid level on the transition from the TR to CBCR is significant. When the liquid level was 0, 5 and 10 cm, the range of superficial gas velocity for the TR was 0.002–0.053, 0.002–0.039 and 0.002–0.029 m/s, respectively. When the liquid height was 15, 20 and 25 cm, the range of superficial gas velocity for the TR was 0.002–0.012 m/s and this did not change with the liquid level. The superficial gas velocity for the transition from the TR to CBCR decreased with increasing unaerated liquid level until a critical liquid level of about 15 cm. Above this critical liquid level, the superficial gas velocity for the transition from the TR to CBCR remained almost unchanged. In a conventional single-stage airlift reactor, the effect of the liquid level is insignificant because the liquid level in a single-stage reactor is always higher than the above critical value, and the BFR and TR only existed at rather low superficial gas velocities ($U_g < 0.012$ m/s for the reactor in this work). However, in a multi-stage reactor, a gas layer forms below the internal in the bottom stage without a gas–liquid separator, and results in dependence of the liquid level both on the reactor structure and operating condition. The liquid level in the bottom stage may decrease to lower than the critical liquid level with an increase in the operating pressure or superficial gas velocity, thus the effect of the liquid level must be properly considered. In addition, the results can also be used to design and operate an internal-loop airlift reactor without a gas–liquid separator.

3.3. *Bubble penetration depth*

The bubble penetration depth in the downcomer depended on the liquid level and superficial gas velocity. It increased with an increase in the superficial gas velocity, and showed different characteristics at different liquid levels. At a higher liquid level, the range of superficial gas velocity for the TR was narrower and the bubble penetration depth in the downcomer increased much more quickly with the superficial gas velocity. This phenomenon is related to the flowing resistance of bubbles from the riser to the downcomer above the draft tube. At a lower liquid level, the flowing resistance above the draft tube was larger due to a decrease in the limited flowing cross-section. At a higher liquid level, the following resistance was smaller due to a larger flowing cross-section.

When the bubble penetration depth is less than the height of the draft tube, i.e., the bubble swarm in the downcomer is in the TR, an empirical correlation for the bubble penetration depth in the downcomer was obtained by fitting the experimental data as:

$$h = 7.26U_g^{0.71}(H+H')^{6.8} \tag{4}$$

where H' is the height of the draft tube ($H' = 1.0$ m in this work) and H is the liquid height above the top of the draft tube. When the predicted value by $h = 7.26U_g^{0.71}(H+H')^{6.8}$ is larger than the height of the draft tube H', the predicted bubble penetration depth is taken as H', indicating that the flow enters the CBCR. A compari-

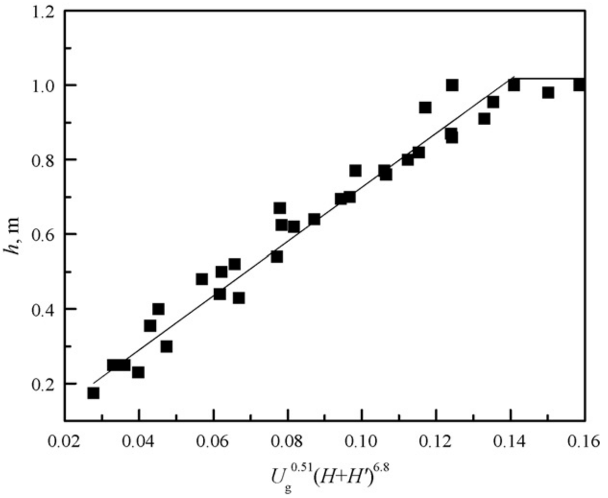


Fig. 7. Comparison of measured bubbles penetration depths with those calculated by Eq. (4).

son of the measured bubble penetration depths and the calculated values from Eq. (4) is shown in Fig. 7. The results showed that the empirical correlation gave satisfactorily calculations of the bubble penetration depth in the reactor of this work.

3.4. Gas holdup

3.4.1. Gas holdup in the downcomer

The effects of the superficial gas velocity and unaerated liquid level on the axial profiles of the gas holdup in the downcomer at unaerated liquid levels of 0, 5 and 10 cm are shown in Figs. 8–10, respectively. The results showed that the axial profile of the gas holdup in the downcomer is non-uniform in the TR, and becomes more uniform when the flow enters the CBCR. For lower liquid levels of 0 and 5 cm, the gas holdups in the downcomer remain almost constant in the range of high superficial gas velocity. However, there is a monotonic but slight increase in the downcomer gas holdup in the range of high superficial gas velocity for liquid level of 10 cm. The reason for this difference is that the liquid level affects entrainment of bubbles above the draft tube from the riser into downcomer.

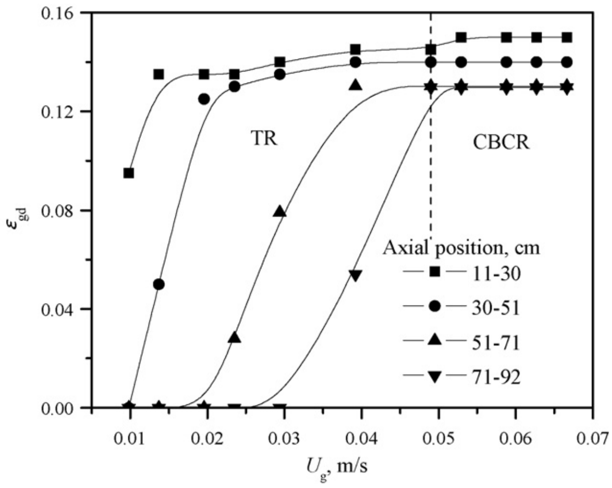


Fig. 8. Effects of the unaerated liquid level on the gas holdups in downcomer at different axial positions ($H = 0$).

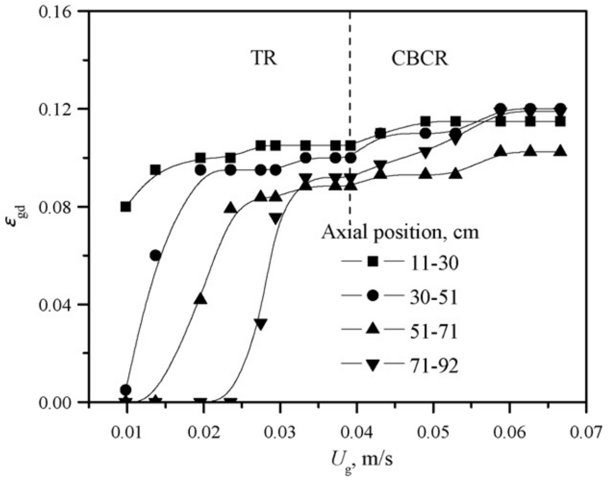


Fig. 9. Effects of the unaerated liquid level on the gas holdup in the downcomer at different axial positions ($H = 5$ cm).

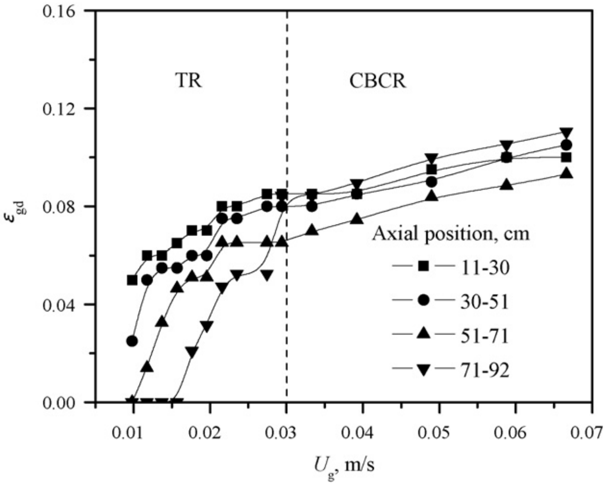


Fig. 10. Effects of the unaerated liquid level on the gas holdup in the downcomer at different axial positions ($H = 10$ cm).

Figs. 8–10 also show that the gas holdup in the downcomer decreased with an increase in the unaerated liquid level, similar to the trend with the gas holdup in the riser, as shown in Fig. 11. With an increase in the liquid height, the liquid circulation velocity increased, which in turn, caused a decrease in the residence time of gas bubbles and a decrease in the gas holdup. Similar results were reported by Seigel et al. [9], Ladwa et al. [15] and Merchuk et al. [16]. However, the axial profiles of the gas holdup and bubble circulation regimes were not studied in their works.

3.4.2. Gas holdup difference between the riser and downcomer

The effects of the superficial gas velocity and liquid level on the average gas holdup in the riser are shown in Fig. 11. It can be seen that the gas holdup increased with increasing superficial gas velocity at a given liquid level. At lower superficial gas velocities, the gas holdup increased almost linearly with increasing superficial gas velocity. At higher superficial gas velocities, the gas holdup slightly increased because of bubble coalescence. Fig. 11 also shows that the gas holdup decreased with an increase in the unaerated liquid level at a given superficial gas velocity. This is because the flowing resis-

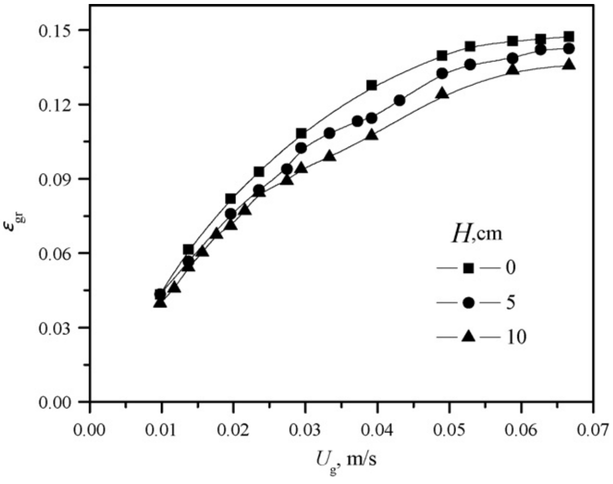


Fig. 11. Effects of the superficial gas velocity and unaerated liquid level on the gas holdup in the riser.

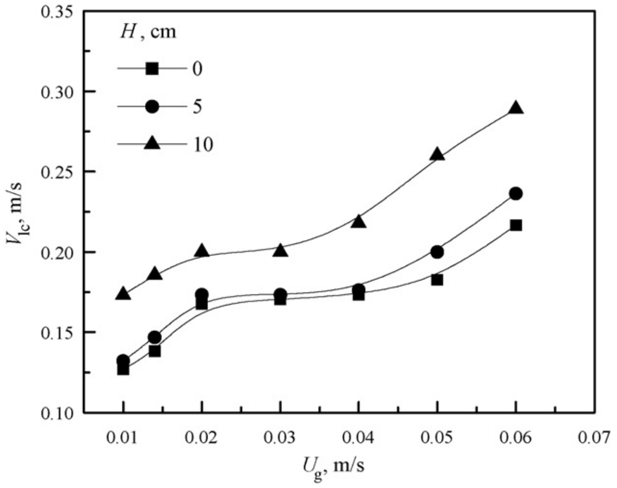


Fig. 13. Effects of the superficial gas velocity and unaerated liquid level on the liquid circulation velocity in the downcomer.

tance above the draft tube decreased with an increase in the liquid level, which resulted in an increase in liquid circulation velocity and a decrease in the gas holdup. Thus, the liquid level affected not only the bubble circulation regimes but also the gas holdup in the riser.

The effects of the superficial gas velocity and unaerated liquid level on the difference in gas holdups in the riser and downcomer are shown in Fig. 12. When the superficial gas velocity increased, the gas holdup difference for $H=0$ or 5 cm did not change much in the TR, but notably increased in the CBCR. The results in TR at the liquid level of 0 cm were exceptional because these showed a significant decrease in the gas holdup difference with the superficial gas velocity in the TR. The reason is that when the liquid level was lower, the flowing resistance above the draft tube decreased with an increase in the superficial gas velocity, more gas bubbles were entrained into the downcomer, thus the gas holdup in the riser increased less than that in the downcomer. A similar phenomenon was reported by van Benthum et al. [11]. From Fig. 12, it can also be seen that the unaerated liquid level has a significant effect on the difference in gas holdups. At lower liquid levels, the difference in gas holdups in the riser and downcomer was much larger.

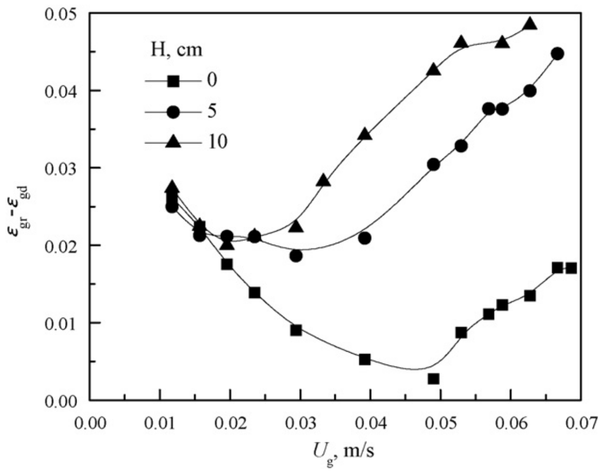


Fig. 12. Effects of the superficial gas velocity and unaerated liquid level on the difference between the gas holdups in the riser and downcomer.

3.5. Liquid circulation velocity

The effects of the superficial gas velocity and unaerated liquid level on the liquid circulation velocity in the downcomer are shown in Fig. 13. With increasing superficial gas velocity, in the TR the liquid circulation velocity first increased, and then remained approximately constant. In the CBCR the liquid circulation velocity increased with increasing superficial gas velocity. The transition liquid circulation velocity corresponded to the regime transition from the TR to CBCR. The difference between the gas holdups in the riser and downcomer is the driving force for the liquid circulation, therefore the liquid circulation velocity usually monotonically increase with the difference of gas holdup. However, there are special cases where the circulation velocity increases with a decrease in gas holdup difference. The reason is that in the TR, the aerated liquid level increases with an increase in the superficial gas velocity, which in turn, decreases the flowing resistance in the region above the draft tube and an increase in the liquid circulation velocity. This effect is more significant at a lower liquid level because the effect of the liquid level on the flowing resistance becomes insignificant at a higher liquid level. When the liquid level exceeded the critical value, the liquid circulation velocity remained unchanged and approximately equal to the bubbles swarm slip velocity.

Fig. 13 also shows that the liquid circulation velocity increased with an increase in the unaerated liquid level. This is because the difference in the gas holdups in the riser and downcomer increased with an increase in the unaerated liquid level, as shown in Fig. 12. In addition, the flowing resistance from above the top of the draft tube to the downcomer decreased with increasing liquid level. Couvert et al. [17] and Kilonzo et al. [18] also observed the same phenomenon. With an increase of the liquid level, the liquid circulation velocity increased at a given superficial gas velocity, which resulted in a much lower superficial gas velocity for the transition from the TR to CBCR. The CBCR can be easily reached at an unaerated liquid level higher than the critical level (15 cm in this work). The design and operation of the multi-stage reactor must account for all the factors that affect the liquid level.

4. Analysis and identification of the bubble circulation regimes

The ratio between the gas holdups in the downcomer and riser ($\varepsilon_{gd}/\varepsilon_{gr}$) is an important parameter, which is related to the driv-

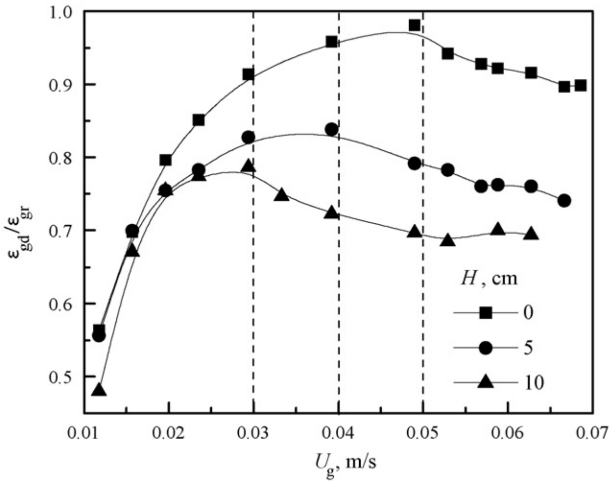


Fig. 14. Effects of the superficial gas velocity and unaerated liquid level on the ratio between the gas holdups in the downcomer and riser.

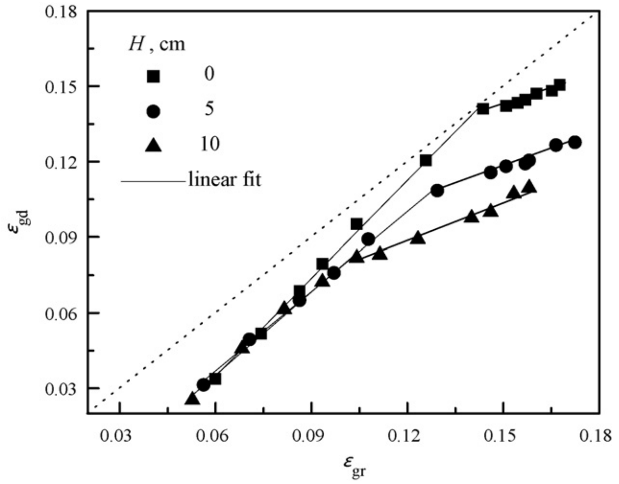


Fig. 15. Relationship between the gas holdups in the riser and downcomer.

ing force of the system. The parameter $\varepsilon_{gd}/\varepsilon_{gr}$ was reported to be constant in the literature [19–21]. However, the results of this work are not in agreement with this conclusion, as shown in Fig. 14. In the BFR, the ratio $\varepsilon_{gd}/\varepsilon_{gr}$ was 0. In the TR, the ratio increased with an increase in the superficial gas velocity and can reach a maximum at the regime transition. In the CBCR, the ratio then decreased with the superficial gas velocity. Fig. 14 also shows that the unaerated liquid level has a significant effect on the maximum value of $\varepsilon_{gd}/\varepsilon_{gr}$, which decreased with an increase in the liquid level. Thus, the regime transition from the TR to BCCR can be identified by the variation of $\varepsilon_{gd}/\varepsilon_{gr}$ with the superficial gas velocity. Based on these criteria, the superficial gas velocities for the transition from the TR to CBCR were 0.050, 0.040 and 0.030 m/s for liquid level 0, 5 and 10 cm, respectively, in accordance with the transition velocities of 0.053, 0.039 and 0.029 determined by experimental observation in Fig. 5.

The bubble circulation regimes can also be identified by the relationship of gas holdups in the riser and downcomer. In a liquid-batch mode, the liquid flowing through the downcomer and riser is equal:

$$V_{lr}A_r(1-\varepsilon_{gr}) = V_{ld}A_d(1-\varepsilon_{gd}) \tag{5}$$

where V_{lr} and V_{ld} are the linear liquid velocity in the riser and downcomer, respectively, ε_{gr} and ε_{gd} are the gas holdups in the riser and downcomer, respectively, and A_r and A_d are the cross-sectional area of the riser and downcomer, respectively. Rearrangement of Eq. (5) yields

$$\varepsilon_{gd} = \frac{V_{lr}A_r}{V_{ld}A_d}\varepsilon_{gr} + \frac{V_{ld}A_d - V_{lr}A_r}{V_{ld}A_d} \tag{6}$$

The relationship of the gas holdup in the riser and downcomer is shown in Fig. 15. The results show that the ε_{gd}–ε_{gr} curve in both the TR and BCCR regimes is linear ($\varepsilon_{gd} = a\varepsilon_{gr} + b$), but the slope in the TR is larger than that in the BCCR. The values of the coefficients a and b for the TR and BCCR are summarized in Table 1. The changes in slope of the ε_{gd}–ε_{gr} curve can thus be used to identify the regimes transition from the TR to BCCR, and the resulted transition superficial gas velocities were 0.053, 0.039 and 0.029 m/s for liquid level 0, 5 and 10 cm, respectively.

Table 1
Values of the parameters a and b in the correlation $\varepsilon_{gd} = a\varepsilon_{gr} + b$ for the TR and BCCR

Liquid height, H (cm)	TR		CBCR	
	a	b	a	b
0	1.294	−0.0427	0.512	0.0643
5	1.054	−0.0263	0.485	0.0445
10	1.098	−0.0305	0.563	0.0197

5. Conclusions

The bubble circulation regimes in the bottom stage of a multi-stage internal-loop airlift reactor were studied. The effects of the liquid level and superficial gas velocity on the bubble circulation regimes, and the liquid circulation velocity, gas holdups in the riser and downcomer and penetration depth of bubbles in the downcomer in each flow regime were investigated.

The unaerated liquid level significantly affected the transition from the TR to CBCR when the unaerated liquid level was lower than a critical liquid level, but had a negligible effect on the transition from the BFR to TR. The gas holdup in the riser decreased with an increase in the liquid level. The axial profile of the gas holdup in the downcomer was non-uniform in the BFR, but almost uniform in the CBCR. With an increase in the superficial gas velocity, the liquid circulation velocity increased in the BFR, remained approximately unchanged in the TR, and then increased in the CBCR. A correlation for predicting the bubbles penetration depth in the downcomer was obtained and a good agreement was obtained between the predicted and experimental values. A mechanism for regime transition that is based on the measured gas holdup, liquid circulation velocity and bubble penetration depth was given, and methods for the identification of the regime transition based on the relationship of the gas holdups in the riser and downcomer were also proposed.

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