Hydrodynamic Considerations in an External Loop Airlift Reactor with a Modified Downcomer

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Hydrodynamic Considerations in an External Loop Airlift Reactor with a Modified Downcomer

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Gas holdup and superficial liquid velocity in the downcomer and riser are studied for an external loop airlift reactor with a downcomer-to-riser area ratio of 1:16. Two downcomer configurations are investigated over a range of superficial gas velocities (0.5 \( \leq U_G \leq 20 \text{ cm/s} \)) using three aeration plate open area ratios (\( A = 0.62, 0.99, \) and 2.22%). These results are compared to a bubble column operated with similar operating conditions. Gas holdup in both the riser and downcomer are found to increase with increasing superficial gas velocity. Results show that riser gas holdup varies slightly with downcomer configuration, while a considerable variation is observed for downcomer gas holdup. The superficial liquid velocity varies considerably for the two downcomer configurations and is a function of superficial gas velocity and flow conditions in the downcomer. Observed variations are independent of aeration plate open area ratio.

Introduction

Studies involving external airlift loop reactors (EALRs) have indicated that reactor geometry is a key factor in determining gas holdup and liquid velocity in the downcomer and riser.\(^1\)–\(^10\) When EALRs are used as biological fermenters, gas holdup and liquid velocity in the riser and downcomer become key hydrodynamic factors that determine if there will be dead zones in the reactor. If the liquid velocity is too slow, dead zones may result and biological growth will cease, reducing the overall reactor productivity. Thus, prior to using an EALR in biological applications, the effect of reactor geometry on EALR hydrodynamics must be fully understood.

Previous investigators have reported that EALR performance depends on such parameters as superficial gas velocity, cross-sectional area ratio of the downcomer and riser, type of gas sparger, horizontal connector geometries, and liquid physical properties.\(^1\)–\(^10\) Most of these previous works have focused on airlift reactors with a downcomer-to-riser area ratio greater than 1:9. As the downcomer-to-riser area ratio decreases, there exists a point when some of the EALR hydrodynamics, such as riser gas holdup, may more closely resemble the hydrodynamics observed in bubble column reactors. For EALR with a downcomer-to-riser ratio greater than 1:9 this is not observed. This current study focuses on a fixed downcomer-to-riser area ratio of 1:16 to determine the effect of reducing the downcomer-to-riser ratio on EALR hydrodynamics.

Experimental Procedures

A schematic of the EALR used in this study is shown in Figure 1 and consists of a 2.4 m acrylic riser (0.10 m internal diameter) and a 2.4 m acrylic downcomer (0.025 m internal diameter). The downcomer and riser sections are connected via two 0.13 m long horizontal acrylic tubes (0.025 m internal diameter) located at \( H = 0.05 \) and 1.27 m, where \( H \) is the reactor height above the aeration plate. The gas phase is injected at the riser base through one of three stainless steel aeration plates having open area ratios of \( A = 0.62, 0.99, \) and 2.22%. For each aeration plate, the change in open area ratio is accomplished by changing the number of uniformly distributed 1 mm diameter holes. A gas plenum is located below the aeration plate and filled with large glass beads to promote uniform gas distribution into the riser.

The riser and downcomer top sections are joined together with a ball valve as they enter the column vent, providing two possible reactor configurations where gas may or may not be allowed to pass through the upper section of the downcomer. Likewise, a gate valve is located in the middle of the downcomer section so that when closed, liquid flow through the downcomer is stopped and the reactor vessel approximates a semibatch bubble column.

All tests are completed at local barometric pressure and room temperature (18–22 °C). The gas phase is compressed air, and the liquid phase is unconditioned tap water. All measurements

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**Figure 1.** Experimental external airlift loop reactor (EALR) schematic.
are carried out batchwise with respect to the liquid phase. The superficial gas velocity \( U_G \) is calculated using the cross-sectional area of the riser and the volumetric gas flow rate that is measured using one of two calibrated mass flow meters, to cover low and high gas flow rates, respectively.

Gas holdup in the riser section \( \varepsilon_r \) is measured between two pressure transducers, installed in the riser at \( H = 0.10 \) and 1.10 m, and determined from the reactor pressure drop assuming that acceleration effects are negligible.\(^{1,10}\) The total pressure drop in the riser corresponds to the hydrostatic head and is related to riser gas holdup. The riser gas holdup measurement was verified by use of the bed expansion method to ensure its accuracy.\(^{12}\)

Gas holdup in the downcomer section \( \varepsilon_d \) is measured using an inclined U-tube manometer which is attached to the downcomer at \( H = 0.05 \) and 0.67 m, where gas holdup is a function of the change in the height of the water columns in the manometer, assuming acceleration effects to be negligible. The downcomer gas holdup measurement was verified using pressure transducers during subsequent testing to ensure accuracy.\(^{12}\)

The liquid linear velocity in the downcomer section is determined using a salt tracer.\(^{13}\) A 2 mL concentrated potassium chloride solution is instantaneously injected into the downcomer at \( H = 1.08 \) m using an air-driven injector system. The liquid conductivity response is recorded at two downstream locations using a pair of identical conductivity probes, located at \( H = 0.63 \) and 0.97 m. Using the measured time interval between the conductivity peaks and the known vertical distance between the probes, the liquid linear velocity in the downcomer is then calculated.\(^{12}\) The use of two identical probes eliminates the need to consider the response time of the electrodes.\(^{1,5,13−16}\)

The potassium chloride salt solution used as a tracer to determine the superficial liquid velocity has been shown in previous bubble column studies to significantly affect bubble coalescence and gas holdup, particularly in the transition region from homogeneous to heterogeneous flow.\(^{13}\) Jamialahmadi and Muller-Steinhagen\(^{17}\) and Zahradnik et al.\(^{18}\) evaluated the effect of salt on reactor hydrodynamics using salt concentrations that ranged from 0.005 to 0.15 g/cm\(^3\) and reported that reactor hydrodynamics were not affected for the lowest concentrations. The salt concentration in the ALR during the outlined testing procedure varies from 0 initially to 0.0004 g/cm\(^3\) at the conclusion of each test, which is an order of magnitude smaller than those reported by others. Thus, the effect of EALR salt concentration on bubble coalescence and gas holdup in this study is assumed to be negligible.

For each of the three aeration plates, the EALR is operated with the downcomer vent open and the downcomer valve open (open vent (OV) mode), with the downcomer vent closed and the downcomer valve open (closed vent (CV) mode), and with both the downcomer vent and downcomer valve closed (bubble column (BC) mode). Note that the downcomer vent is opened or closed with component 2 in Figure 1, and the downcomer valve is opened or closed with component 11. For the bubble column mode, visual observations confirmed that the EALR was indeed operating as a bubble column when the respective values were closed.

Changes in operation mode and inlet superficial gas velocity alter the observable flow patterns in the EALR. The changes in observed flow patterns are quantified using high-speed digital photography. Photographs documenting the fluid flow behavior in the upper and lower tube connectors were taken for all operational conditions considered. A detailed review and presentation of them is available elsewhere.\(^{12}\)

Measurement uncertainties are estimated following the method provided by Figliola and Beasley.\(^{19}\) The typical uncertainties associated with \( U_G \) and \( V_d \) are ±1−5% and ±1−8%, respectively, with the larger uncertainties corresponding to the lowest velocity measurements. The corresponding absolute gas holdup uncertainty is estimated to be ±0.001−0.015.

**Results and Discussion**

**Hydrodynamic Observations.** When operated in the CV mode, a large gas pocket forms in the upper horizontal connection as soon as gas is sparged into the reactor at \( U_G = 0.5 \) cm/s, the lowest \( U_G \) considered (Figure 2a). Similar results were also noted by Choi\(^{19}\) for a comparable reactor. The gas pocket size in the horizontal connector varies slightly during the experiments, but no significant change is observed over the range of \( U_G \) studied. After the initial formation of the gas pocket, a gas bubble forms just below the horizontal connector in the downcomer as \( U_G \) increases. This gas bubble, when present, is located between the horizontal connector and entrainment region. As \( U_G \) increases, the gas bubble diameter grows until it is nearly equal to the downcomer internal diameter, and then the gas bubble length increases with \( U_G \), as shown in Figure 2b.

Visual observations indicate that, with the exception of a few very small bubbles, the liquid in the downcomer below the gas pocket is free of entrained gas over the entire \( U_G \) range, indicating that gas separation occurs as the gas−liquid mixture moves through the horizontal connector. Similar trends were reported in work done by others.\(^{4,9}\) Below the gas bubble in

![Figure 2. Gas pocket and bubble locations in the EALR when the downcomer vent is closed (CV mode): (a) restricted flow regime \( (U_G = 0.5 \text{ cm/s}) \) and (b) fully restricted flow regime \( (U_G = 20 \text{ cm/s}) \).](image)
At very low superficial gas velocities most of the gas phase that enters the horizontal connector rises to the top of the connector and exits up through the downcomer vent. As $U_G$ increases, the number and size of gas bubbles in the downcomer increase due to a reduction of phase separation as the liquid momentum in the horizontal connector increases. Gas bubble formation in the downcomer begins at $U_G \approx 3.5$ cm/s when the fluid velocity around the elbow in the upper portion of the downcomer is fast enough to cause liquid separation from the downcomer walls. The gas bubble diameter and length increase with $U_G$ for $3.5 \leq U_G \leq 10$ cm/s. When $U_G \geq 10$ cm/s, the gas bubble size rapidly oscillates with a mean size that appears to be independent of $U_G$; the cause of this rapid oscillation in size is thought to be due to variations in the rate of gas entrainment below the gas bubble and the periodic gas venting up the downcomer.

**Gas Holdup.** To study the effect of $U_G$ on gas holdup in the EALR, the reactor is operated in the OV and CV modes and compared to the BC mode. The effect of EALR operational mode on gas holdup is shown in Figure 4 for $A = 0.62\%$. When $U_G < 3.5$ cm/s, the operational mode has a negligible effect on $\epsilon_r$. When $U_G \geq 3.5$ cm/s, there appears to be slight differences in $\epsilon_r$, but this variation is small, and in some cases, the degree of variation is not more than the expected measurement error. It is apparent that aside from minor variations in magnitude, $\epsilon_r$ is, at most, a weak function of EALR operational mode for the given reactor geometry. Similar results are observed for $A = 0.99$ and $2.22\%$. The observed lack of operating condition influence on gas holdup is contrary to the previously published results of Bentifraouine et al.\(^{20}\) and Choi\(^1\) who reported that gas holdup increased when the downcomer was not vented to the atmosphere. This difference in observed behavior is attributed to the smaller 1:16 downcomer-to-riser area ratio, resulting in an EALR that behaves more like a bubble column than a loop reactor with regard to $\epsilon_r$. As a result this particular EALR has the benefit of liquid circulation around the loop and $\epsilon_r$ that more closely resembles that of a bubble column. This combination of features may be of interest in biological applications as the increase in gas holdup will increase cell and gas contacting time without creating dead zones.

It should be noted that $\epsilon_d$ is only shown for the OV mode in Figure 4 because $\epsilon_d$ is negligible when the EALR is operated in the CV mode and nonexistent for the BC mode. For $U_G < 2$ cm/s, $\epsilon_d \approx 0$, which agrees with visual observations made at
these operating conditions. When \(2 \leq U_G \leq 10 \text{ cm/s}, \varepsilon_d\) sharply increases with \(U_G\). Further increases in \(U_G\) result in no change in \(\varepsilon_d\). Note that, for most cases, \(\varepsilon_d\) is approximately three times smaller than \(\varepsilon_r\) for the OV mode and \(\varepsilon_d \approx 0\) for the CV mode.

**Liquid Circulation.** The bulk density difference of the two vertical columns in an EALR provides the driving force for liquid circulation (i.e., \(U_{Lr}\) and \(U_{Ld}\)). At steady-state conditions, the driving force is balanced by reactor flow losses due to fluid friction and changes in reactor geometry.\(^{13,21-24}\) Thus, as the difference between \(\varepsilon_r\) and \(\varepsilon_d\) increases with increasing \(U_G\), the driving force must also increase due to bulk density changes associated with changing gas holdup, creating a potential for \(U_{Lr}\) to increase. However, in practice, \(U_{Lr}\) may increase or decrease with \(U_G\), depending on how the reactor flow losses change with \(U_G\). Hence, \(U_{Lr}\) is considered largely a function of \(U_G\) and reactor geometry.

The effect of \(U_G\) on \(U_{Lr}\), as a function of aeration plate open area ratio and mode of operation, is shown in Figure 5. The aeration plate open area ratio has a minimal effect on \(U_{Lr}\) for both modes of operation. The mode of operation, however, has a significant effect on \(U_{Lr}\). When the EALR is operated in the OV mode, \(U_{Lr}\) increases to a local maximum and then decreases sharply as \(U_G\) increases, and eventually becomes independent of \(U_G\). As a result, three liquid flow regimes are identified for the OV mode of operation: (i) unrestricted flow, (ii) restricted flow, and (iii) fully restricted flow.

In the unrestricted flow regime, \(U_{Lr}\) increases sharply with increasing \(U_G\). This initial increase in \(U_{Lr}\) corresponds to the rapid rise in \(\varepsilon_r\) and a much smaller rise in \(\varepsilon_d\). Hence, when \(U_G \approx 3.5 \text{ cm/s}, \ U_{Lr}\) is primarily a function of the bulk density difference; this observation agrees with the experimental results presented by others.\(^{13,21-24}\)

When the bulk density difference (\(\varepsilon_r - \varepsilon_d\)) is plotted as a function of \(U_{Lr}\) (Figure 6), the relationship between the driving force and liquid circulation becomes evident, and the liquid flow regimes and their transition points can be identified. Figure 6 shows that the shift from the unrestricted flow regime to the restricted flow regime occurs at \(U_{Lr} \approx 3.7 \text{ cm/s}, \) which roughly corresponds to the point where bubble formation is usually observed in the downcomer\(^{12}\) and the local maximum seen in Figure 5. As noted earlier, stationary gas bubble formation in the top of the downcomer begins at \(U_G \approx 3.5 \text{ cm/s}\).

Increasing \(U_G\) in the restricted flow regime results in a decrease in \(U_{Lr}\). Figure 6 also shows that \(U_{Lr}\) decreases in this regime as the bulk density difference increases, which is contrary to the observations made for the unrestricted flow regime. Hence, in the restricted flow regime, \(U_{Lr}\) is a function of the flow losses, geometry, and driving force and the flow losses are considered to dominate in this flow regime. The dominance of the flow losses are attributed to stationary gas bubble growth in the downcomer, which causes the flow losses to increase rapidly with \(U_G\). Initially, the stationary gas bubble begins to grow (\(3.5 \leq U_G \leq 5 \text{ cm/s}\)), and the effective downcomer-to-riser aspect ratio decreases, creating a choked flow condition in the downcomer that decreases \(U_{Lr}\) (Figure 5). As \(U_G\) continues to increase (\(5 \text{ cm/s} \leq U_G \leq 10 \text{ cm/s}\)), the bubble length increases until it reaches a maximum length when \(U_G \approx 10 \text{ cm/s}\). The change in the stationary gas bubble length for \(U_G < 10 \text{ cm/s}\) is a direct result of the bulk density difference in the riser and downcomer and the liquid separation that occurs as the fluid enters the downcomer. Hence, even though the driving force increases, the flow losses increase faster with \(U_G\), causing \(U_{Lr}\) to decrease. Essentially, the downcomer flow has become choked.

When the EALR is operated in the CV mode, the \(U_{Lr}\) trends as a function of \(U_G\) (Figure 7) are limited to the later two flow regimes discussed for the OV mode operation. As discussed in the hydrodynamic observations, a gas pocket forms immediately in the horizontal connector for the lowest \(U_G\) and a stationary gas bubble forms in the downcomer soon after as \(U_G\) increases, causing the EALR to operate in the restricted flow regime. It is worth noting that even though \(\varepsilon_d\) exists for this mode of operation, the magnitude is so small that it cannot be measured with any degree of accuracy, and thus is considered negligible. The driving force for the CV mode of operation becomes solely a function of \(\varepsilon_r\), unlike the OV mode where the driving force is a function of the difference between \(\varepsilon_r\) and \(\varepsilon_d\).

For the CV mode of operation shown in Figure 7, the restricted flow regime is separated into a decreasing and increasing restricted flow regime. Initially, as \(U_G\) increases, the fluid flow is characterized as decreasing restricted flow where, as shown in Figure 5, \(U_{Lr}\) decreases with increasing \(U_G\). This decrease in \(U_{Lr}\) continues until a local minimum is reached at \(U_G \approx 7 \text{ cm/s}\), which corresponds to \(\varepsilon_r \approx 0.18\) (Figure 4). The decrease in \(U_{Lr}\) in this regime is again attributed to the development and growth of the stationary gas bubble in the downcomer. Once the minimum \(U_{Lr}\) is reached, \(U_{Lr}\) begins to increase with increasing \(U_G\), switching the flow regime to

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**Figure 5.** Aeration plate open area ratio and mode of operation effects on riser superficial liquid velocity.

**Figure 6.** Relationship between the driving force (\(\varepsilon_r - \varepsilon_d\)) and the superficial liquid velocity as a function of aeration plate open area ratio for the open vent mode external airlift loop reactor operation.
the increasing restricted flow regime. In this flow regime, $U_{Ld}$ continues to increase with $U_G$ and $\varepsilon_t$ until $U_G \approx 14$ cm/s and $\varepsilon_t \approx 0.24$. It is important to note that the stationary gas bubble growth is observed to be relatively constant as $U_G$ increases through both restricted flow regimes, indicating that, for the decreasing restricted flow regime, flow losses initially exceed the increase in the driving force. This effect then reverses as the flow regime changes to increasing restricted flow, indicating that, in this regime, the driving force is larger than the flow losses.

Although $U_{Ld}$ is independent of aeration plate open area ratio (Figure 5), the onset of the fully restricted flow regime for the CV mode is influenced by the aeration plate open area ratio (Figure 7). This shift from the increasing restricted flow regime to the fully restricted flow regime occurs at $U_G \approx 13$ cm/s for $A < 1\%$ (Figure 7). For $A = 2.22\%$, the transition into the fully restricted flow regime occurs at $U_G \approx 19$ cm/s, but more data with $U_G > 20$ cm/s is needed to fully understand the transition location for the CV mode of operation when $A = 2.22\%$. As discussed for the OV mode of operation, $U_{Ld}$ in the fully restricted flow regime is independent of $U_G$.

The results presented in Figures 6 and 7 clearly show the importance of the gas separator geometric design. The difference in magnitude and behavior of $U_{Ld}$ as a function of $U_G$ for OV and CV modes of operation are a direct result of the degree of bubble disengagement in the gas separator and the geometric design of the separator. One of the primary differences between the OV and CV modes of operation is the flow of disengaged gas. In the case of the CV mode of operation, any gas that disengages in the downcomer and upper horizontal connector immediately build up and then move in a direction opposite that of the liquid flow, resulting in a direct reduction of $U_{Ld}$ (Figure 7). In both OV and CV modes of operation when gas buildup occurs just below the horizontal connector in the downcomer, the open cross-sectional area of the downcomer is reduced, changing the effective downcomer-to-riser area ratio, again resulting in a lower $U_{Ld}$, as shown in Figure 7.

Conclusions

Gas holdup and liquid superficial velocity results were presented for an external loop airlift reactor with a downcomer-to-riser area ratio of 1:16. Three modes of operation (open downcomer vent, closed downcomer vent, and bubble column modes) were studied over a range of aeration plate open areas ratios ($A = 0.62, 0.99,$ and $2.22\%$) and superficial gas velocities ($U_G \leq 20$ cm/s). Geometry changes due to flow restrictions and mode of operation significantly affected the fluid flow hydrodynamics in the EALR. Riser gas holdup was observed to be independent of aeration plate open area ratio and mode of operation. Downcomer gas holdup was only significant when the EALR was operated with the downcomer vent open (OV mode). Three liquid flow regimes were identified for the riser superficial liquid velocity: (i) unrestricted flow, (ii) restricted flow, and (iii) fully restricted flow regimes. For open and closed vent downcomer operation (OV and CV modes), riser superficial liquid velocity was independent of aeration plate open area ratio and strongly dependent on mode of operation. For OV and CV modes, riser superficial liquid velocity was a function of superficial gas velocity in the unrestricted and restricted flow regimes, and independent of superficial gas velocity in the fully restricted flow regime. Hence, for this downcomer-to-riser area ratio, the gas holdup was more like that of a bubble column but significant riser liquid velocity was still recorded; this may be advantageous to certain bioreactors.

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Nomenclature

$A =$ aeration plate open area ratio, $\%$
$BC =$ bubble column
$CV =$ closed vent
$EALR =$ external airlift loop reactor
$H =$ column height, m
$OV =$ open vent
$U_G =$ inlet superficial gas velocity, cm/s
$U_{Ld} =$ downcomer superficial liquid velocity, cm/s
$U_L =$ riser superficial liquid velocity, cm/s

Greek Symbols

$\varepsilon_d =$ downcomer gas holdup
$\varepsilon_t =$ riser gas holdup

Literature Cited