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STUDY OF HYDRODYNAMICS AND MIXING IN AN AIRLIFT REACTOR WITH AN ENLARGED SEPARATOR USING MAGNETIC TRACER METHOD

Jaroslav KLEIN, António A. VICENTE and José A. TEIXEIRA

Centro de Engenharia Biológica, Universidade do Minho, Campus de Gualtar, 4710-057 Braga, Portugal
e-mail: jateixeira@deb.uminho.pt

ABSTRACT

The magnetic tracer technique was used to obtain essential information on hydrodynamics, mixing and reactor design in a multiphase airlift reactor with an enlarged separator. The tracer method involving the use of a magnetic particle as a neutrally buoyant flowfollower allowed measurement of the residence time of the tagged particle in all reactor sections (riser, downcomer, separator and bottom sections). Knowing the settling velocity of the tagged particle, the liquid circulation velocity was also determined. The effects of the design of the enlarged separator (H_{DT}/H_C), of the riser to downcomer cross-sectional area ratio (A_D/A_R) and of the liquid level in the head zone (H_T) were investigated. The hydrodynamics of the ALR was affected by all design parameters. The results of experiments with different heights of draft tube demonstrated how easily various operating flow patterns can be achieved ranging from typical flow patterns for an internal-loop ALR with high downcomer gas holdup to those of an external-loop with low or nil one. On the base of histograms of the residence time of the tagged particle in the separator zone and visual observations, three flow patterns of the particle were described. The RTDs of the tracer particle were also used for assessment the mixing efficiency of reactor sections. The results showed that the best option for the design of ALR with an enlarged separator concerning mixing intensity is the use of reactor configuration with a dual separator and an area ratio A_D/A_R around 4.

INTRODUCTION

The internal-loop airlift reactor with an enlarged separator zone belongs to a class of promising multiphase contactors for chemical and biotechnological processes, where an intimate contact of two (gas-liquid) or three (gas-liquid-solid) phases is required. In view of the separator design, internal-loop airlift reactors are conventionally divided into ALRs without separator (when the separator diameter is equal to the diameter of the outer column – $D_{SEP} = D_C$) and ALRs with separator ($D_{SEP} > D_C$) [1]. Moreover, in the ALR with an enlarged head zone different separator configurations can be obtained by adjusting the length of the draft tube. Thus, two basic constructions of the ALR are considered, depending on whether the upper edge of the draft tube is situated in the enlarged or the narrow part of the separator zone ([2] and see also Fig. 1). The first configuration is named ALR with simple enlarged separator and in the second case ALR with "dual" separator. Its duality lies in the fact that although such a reactor configuration belongs to the group of the ALR with separator (according to the conventional terminology), in view of low bubble separation efficiency this is in fact the ALR without separator [2].

An airlift reactor (ALR) with an enlarged dual separator, seldom referred in literature (e.g. [3-7]), may provide an efficient retention of both solid particles (in the enlarged part of separator) and gas bubbles (in the narrow part) inside the reactor making such a type of reactor particularly attractive for continuous high cell density biosystems [8]. This advantage of the ALR contactors basically results from the existence of a liquid circulation loop inside the reactor originating from the density difference established between the riser and downcomer sections. The liquid circulation velocity is an essential parameter in the design of the ALR reactor because of its crucial effect on various subprocesses – mixing, extent of bubble recirculation, efficiency of solids suspension and distribution of gas and solids holdups. Thus, the knowledge of the liquid circulation rate is of a particular importance. By using a tagged particle and knowing its behaviour (RTD, velocity in all reactor sections, etc.), essential information on all important hydrodynamic parameters and also mixing can be obtained.

The main goal of this study was to utilize a magnetic tracer technique for obtaining information on the residence time of the tagged particle in all reactor sections (riser, downcomer, bottom and separator) independently of each other. Different lengths and diameters of the draft tube and liquid levels in the separator were tested to show how the separator design affects hydrodynamic performance of a two-phase internal-loop airlift reactor.

EXPERIMENTAL

A 50 dm^3 internal-loop airlift reactor with an enlarged degassing zone (0.44 m in diameter and 0.35 m in height) was used for hydrodynamic measurements (see Fig. 1). The height (H_C) and diameter (D_C) of the outer column was 2 and 0.14 m, respectively. The diameter ratio of head zone to outer column was 3.1. Five reactor configurations were used using different diameters and lengths of inner tubes labelled by C1 to C5 (see Table 1). The liquid level above the draft tube (H_T) varied from 0.09 to 0.48 m, for the reactor configurations C1-C5 was kept at the highest level of 0.48 m. The reactor was designed to keep the volume level constant at 50 dm^3 corresponding to the H_T=.0.48 m.

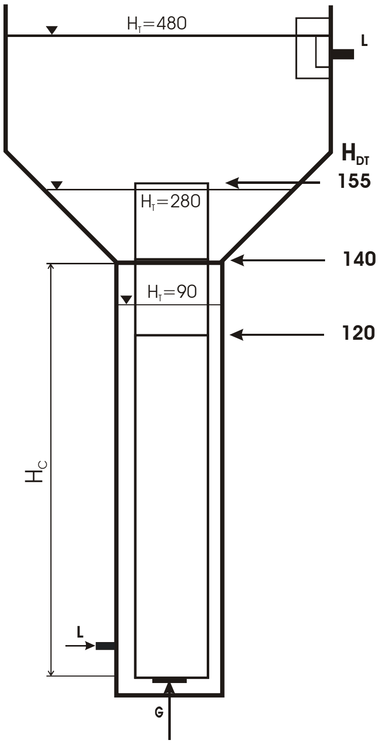

Figure 1. Scheme of the airlift reactor used in experiments with different liquid levels, H_T (in mm) and the height of draft tube, H_{DT}.

Table 1. Basic reactor dimensions used in this study (D_R – inner riser tube diameter, A_R – riser cross-sectional area, A_D – downcomer cross-sectional area, H_{DT} – height of the draft tube, H_T – height of the liquid level in the head zone, H_C – height of lower part of the column).

Label	D_R [m]	A_D/A_R [–]	H_{DT} [m]	H_T [m]	H_{DT}/H_C [–]
C1	0.092	1.2	1.55	0.48	1.11
C2	0.092	1.2	1.40	0.48	1.00
C3	0.092	1.2	1.20	0.48	0.86
C4	0.084	1.7	1.20	0.48	0.86
C5	0.062	4.0	1.20	0.48	0.86
C6	0.092	1.2	1.20	0.28	0.86
C7	0.092	1.2	1.20	0.09	0.86

In all the experiments, water and air were used as the liquid and gas phases, respectively. The experiments were carried out at the temperature of 19±1 °C and atmospheric pressure. Air injection was made 0.061 m below the bottom of the draft tube by means of a perforated plate with a diameter of 0.03 m, with 30 holes of 1 mm each. The air flow rate was controlled by means of rotameters and ranged from 2 up to 70 dm^3/min (referred to 1 atm and 20 °C). The air flow rate was given as the characteristic superficial velocity referred to the column diameter (D_C) calculated for the conditions in the geometric centre of the column, U_{Gc}. The gas holdup was determined by the manometric method. Inverse manometric tubes were used for the measurement of pressure differences between two points in the riser and the downcomer of the ALR. Then, the average overall gas holdups, ε_{GR} and ε_{GD}, were calculated.

A tracer method with a magnetic particle (with high magnetic permeability) as a flowfollower was used [9] to determine residence time of the tagged particle in all individual sections of the airlift reactor (riser, downcomer, separator and bottom zones). The calibration procedure showed that the experimental data on residence time of the particle could be simply used for determining the liquid circulation velocity if the accurate value of the particle velocity is known [9, 10]. The density of the magnetic particle was adjusted to be very close to that of the liquid medium, resulting in a very low terminal settling velocity (up to 1 cm.s^{-1}), when compared to the magnitude of liquid circulation velocities achieved in the reactor.

Statistic data on residence time distribution (RTD) of the tagged particle can be also used to estimate the mixing behaviour of the reactor as a whole and in its individual sections. The relative standard deviation of RTD of the particle can be used to assess the intensity of turbulence in considered reactor section. Moreover, as the mean and variance values of RTD of the tagged particle are known, both Peclet number (Pe) and axial dispersion coefficient (D_Z) can be determinated. According to the axial dispersion model for alrger extents of dispersion, the variance can be expressed for open vessel as follows [11]:

$$\sigma_\theta^2 = \frac{\sigma^2}{t^2} = \frac{2}{Pe} + 8\left(\frac{1}{Pe}\right)^2 \tag{1}$$

Pe number can be determined as:

$$Pe = \frac{V\ L}{D_z} \tag{2}$$

Here V is linear velocity and L is distance between two measuring points.

Pe and D_Z for the whole reactor were calculated from the data of total average circulation time, t_C.

RESULTS

Effect of liquid level in separator (H_T)

It is worth to notice that a modification of liquid level in the enlarged head zone does not change only the liquid volume for bubble separation but also the design of the separator zone (see Fig. 1). While the increase of liquid level in the separator zone (H_T) had only a slight negative effect on the riser holdup (ε_{GR}), the decrease of the downcomer holdup (ε_{GD}) was clearly noticeable (see Fig. 2).

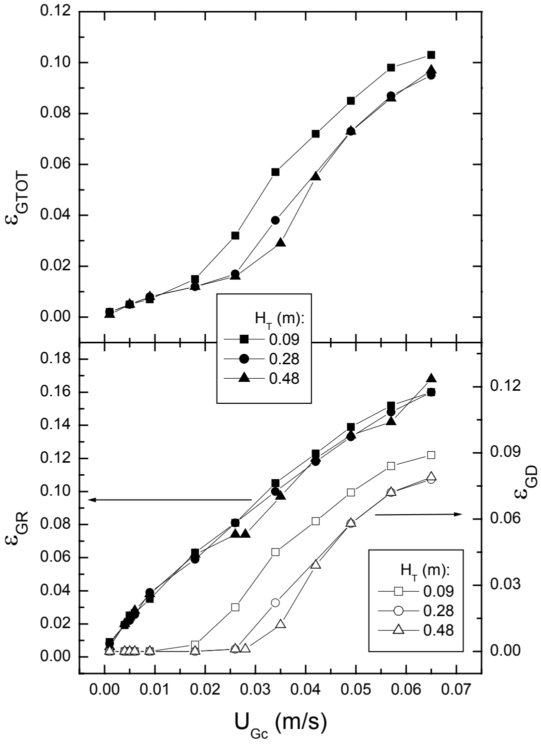

Figure 2. Gas holdup in the riser, the downcomer and the whole reactor as a function of superficial gas velocity U_{Gc}. Data series represent the liquid height in the separator zone, H_T. These results refer to the ALR configuration C5 at different liquid levels.

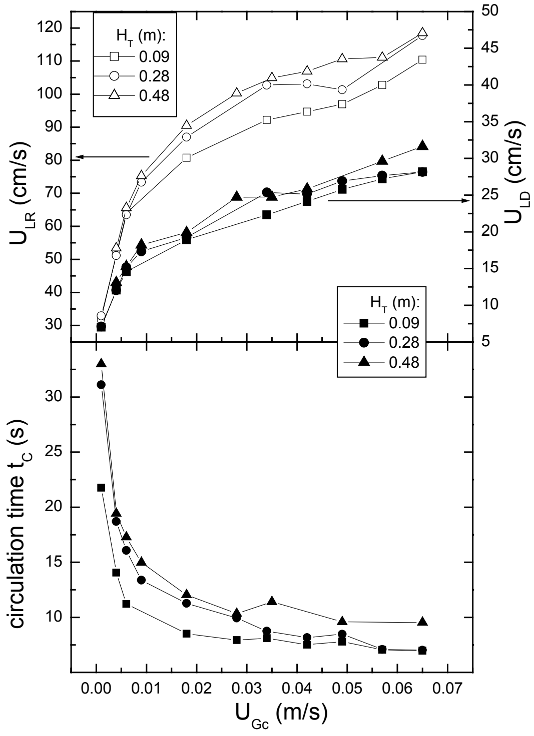

Figure 3. Superficial liquid velocity in the riser (U_{LR}) and downcomer (U_{LD}) and overall circulation time (t_C) as a function of gas superficial velocity, U_{Gc}. Data series represent the liquid height in the separator zone, H_T. These results refer to the ALR configuration C5 at different liquid levels.

The overall gas holdup calculated as the averaged value of holdups in the riser and the downcomer reached the highest value for the lowest liquid level, H_T, equal to 0.09 m. The liquid velocity in both main sections (riser and downcomer) increased with increasing H_T value (see Fig. 3). The effect of the liquid level in the head zone on a liquid circulation was attenuated with growing H_T value. On the contrary, the liquid level had a positive influence on overall liquid circulation time (t_C) due to a strong increase of the residence time of the tagged particle in the separator zone.

If the averaged liquid flow rate Q_L in the main liquid loop (riser-downcomer) is compared for the ALRs with same A_D/A_R (equal to 1.2) and H_{DT} (equal to 1.2 m) (see C3, C6, C7 in Table 1) parameters, no significant effect of the liquid level H_T was observed (Fig. 4). However for the ALRs with A_D/A_R = 4.0, liquid circulation slightly increased with the raise of H_T (not shown). It must be stressed that as the level of the gas-liquid dispersion reached the enlarged part of separator (i.e. for H_T > 0.35 m), H_T did not have any significant effect on ALR hydrodynamics. It can be concluded that the impact of liquid level in the separator zone on the ALR hydrodynamics is based mainly on its effect on holdup in downcomer. Variations of H_T do not significantly change average circulation velocity in the main ALR loop; however, they affect the residence time of the tagged particle in the enlarged head zone and thus the overall circulation time.

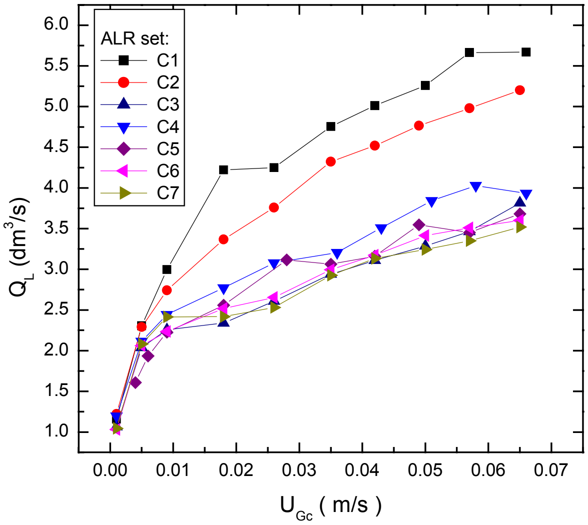

Figure 4. Average liquid flow rate (Q_L) in the main circulation ALR loop versus the gas superficial velocity, U_{Gc}. For explanations of labels C1-7, see Table 1.

Effect of separator design (H_{DT}/H_C) and area ratio A_D/A_R

The modification of the separator design as a consequence of a change of the draft tube height strongly affected primarily the bubble-separation efficiency and, by this means, the overall reactor hydrodynamics (Figure 5).

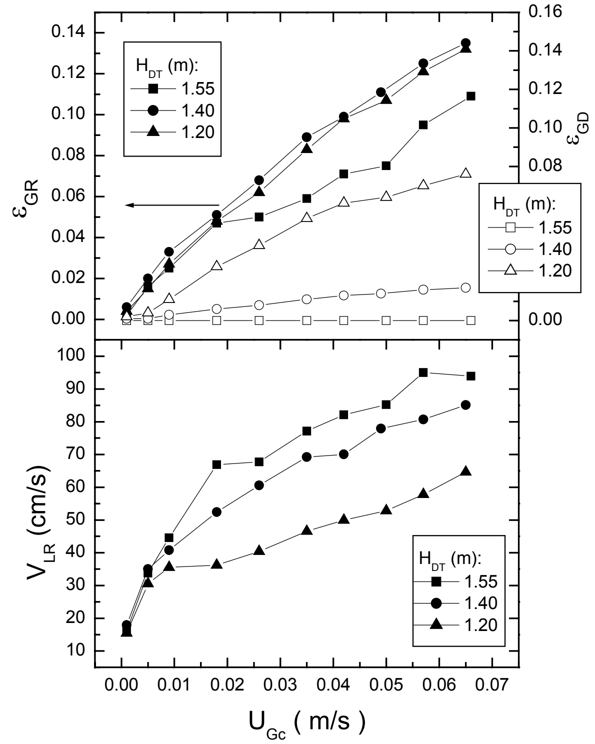

Figure 5. Effect of draft tube height (H_{DT}) on the gas holdup in the riser and downcomer sections and on the linear liquid velocity in the riser as a function of air superficial velocity (see also Table 1).

While the dual separator zone (its narrow part) ensures high downcomer and total gas holdups inside the ALR already at low gas flow rates, the reactor configuration with the longest draft tube separates perfectly the bubbles in the head zone even at the highest gas flow rates. Thus, the increase of the draft tube height due to the increased driving force generates faster net liquid circulation. This confirms also the results of graph in Fig. 4, where the highest liquid flow rate in the reactor circulation loop (Q_L) was reached for the ALR configuration C1. The circulation flow rate was lower by 10 % for the C2 reactor configuration and by 31 % for the C3 reactor configuration, in average.

The effect of the area ratio A_D/A_R (C3-C5 configurations) was not so evident as in the case of the H_{DT}/H_C effect. The changes of the overall circulation velocity V_{LC} (calculated from average circulation time) and the gas holdups in the riser and the downcomer with air flow rate are depicted in Fig. 6.

As can be seen, both partial gas holdups in riser and downcomer increased, as expected, in the whole range of air superficial velocity applied. However, for ε_{GD} an initial plateau was observed due to the fact that only at higher values of air flow rate the entrainment of bubbles into the downcomer occurred. The energy demand for bubble penetration into the downcomer increased consecutively from the reactor configuration C3 to C5, indicating a negative effect of the A_D/A_R ratio. A particular course of the ε_{GD} was found detected for the C5 reactor configuration, where a perfect bubble separation in the head zone was observed up to fairly high U_{Gc} values (< 0.025 m.s^{-1}). At higher flow rates, gas holdup began to build-up very fast reaching the ε_{GD} values for the C3 configuration (with the lowest A_D/A_R ratio) at the highest U_{Gc} values. The highest values of the riser holdup were reached in the ALR with the highest A_D/A_R ratio (C5 configuration) despite the fact that the liquid moved up in the riser section much faster than in the ALR with larger draft tube, e.g. about three times faster than for the C3 reactor configuration. On the contrary, the highest gas content in the downcomer section (ε_{GD}) was found for the reactor with the lowest A_D/A_R ratio (C3 configuration).

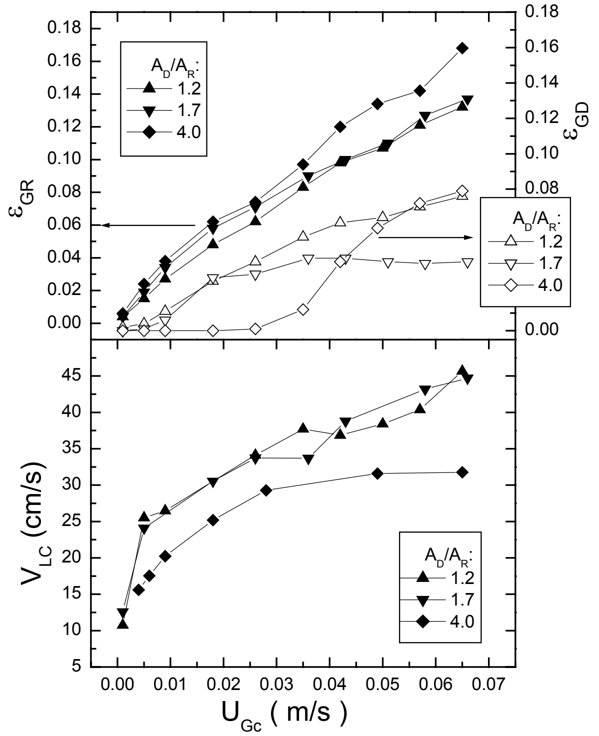

Figure 6. Effect of the area ratio (A_D/A_R) on the gas holdup in the riser and downcomer sections and liquid circulation velocity as a function of gas superficial velocity, U_{Gc} (see also Table 1).

The overall velocity (V_{LC}) calculated from the average circulation time was almost identical for A_D/A_R equal to 1.2 and 1.7, while for the highest A_D/A_R ratio the lowest V_{LC} values were obtained. The liquid circulation flow rate (Q_L) determined as an averaged flow rate in the riser and downcomer sections, showed that the optimal A_D/A_R value to reach the highest circulation velocity in ALR is around 1.7 (see Fig. 4). Any change of A_D/A_R (up or down) worsens liquid circulation. The increase of A_D/A_R , on one hand increases the driving force, but on the other hand, significantly increases the friction losses. On the contrary, the decrease of A_D/A_R decreases the friction losses, but it decreases the driving force as well.

Flow patterns of tagged particle in separator

On the base of histograms of the residence time of the tagged particle in the dual separator zone and visual observations, three flow patterns of the particle in the separator zone were found (Fig. 7). For the first pattern, the particle is entrained by the prevailing liquid flow directly into the downcomer corresponding to the most frequent count of the lowest RTD values. The second flow pattern of the particle is determined by its presence in the turbulent narrow part of the separator zone, just above the top of the draft tube. The last flow pattern is represented by the highest values of the residence time corresponding to the particle residence in the upper enlarged zone of separator. If the values of the total circulation time (t_C) corresponding only to the direct 180° turn of the tagged particle from the riser to downcomer were extracted, almost identical values of t_C independently of the liquid level in the separator (H_T) used would be found (for a comparison, see Fig. 3). This also suggests that the large scatter of original t_C values is mainly caused by fluctuations of the liquid flow in the separator zone.

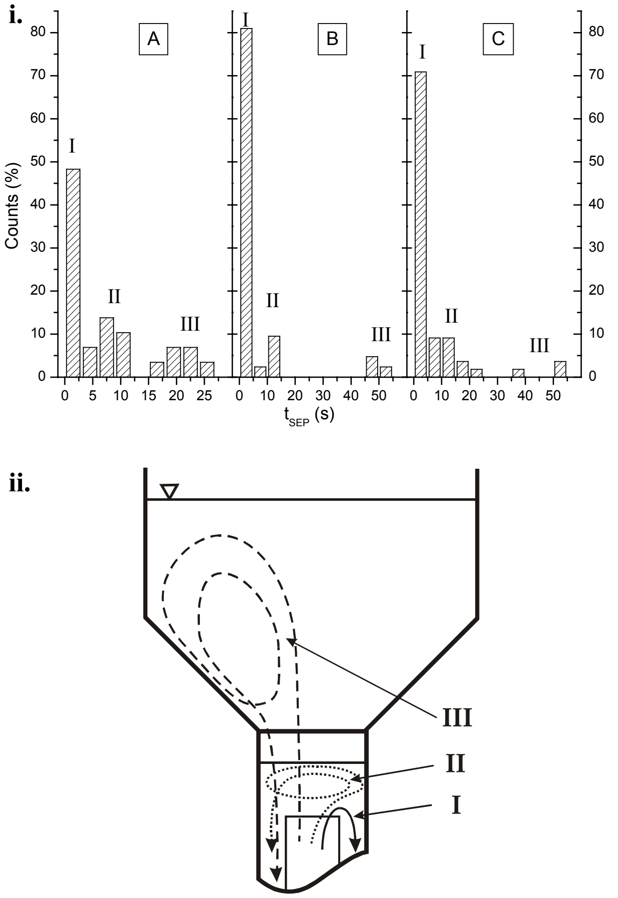

Figure 7. i. Histograms of RTD of tagged particle in separator zone of the ALR with C3 configuration at different U_{Gc} values: A. 0.018, B. 0.035 and C. 0.065 m/s. **ii**. Visualisation of flow patterns based on the RTD histograms. For explanation of indexes I-III, see figure i. above.

Mixing in ALR

The measuring technique allows a comfortable collection of statistically sufficient amount of RTD data in all reactor sections. Then the main statistic parameters (mean, standard deviation and variance) can be used for evaluation of mixing in the ALR. As the first, a relative standard deviation RMS (root mean square) was calculated, which magnitude is proportional to the intensity of turbulence. Evaluation of the results showed that as the H_{DT} increased the intensity of turbulence in both the downcomer and riser zones decreased. This effect was more pronounced in the downcomer part, where the decrease of amount of bubbles was stronger with increasing H_{DT}. This implies that the presence of gas bubbles substantially contributes to the intensity of fluid turbulence. The negative effect of the A_D/A_R ratio on the intensity of turbulence was the same in both riser and downcomer sections. This perhaps was due to different reasons. As the diameter of the riser draft tube decreased, the liquid velocity increased significantly, which dominated over axial mixing (see Peclet´s number evaluation below). In case of the downcomer, the increase of its equivalent diameter (when A_D/A_R increases) caused a lower content of gas bubbles in this section resulting in a lower mixing intensity.

Mixing characteristics of the airlift reactor and its individual sections was also assessed from *Pe* number and dispersion coefficient D_Z calculated using the eqns. (1) & (2). The range of determined values of the *Pe* number for different air flow rates and design parameters are shown in Table 2.

Table 2. Range of *Pe* numbers at different air flow rates and for various ALR configurations calculated for the whole reactor and for its individual sections. For details of reactor configurations C1-C7, see Table 1.

ALR label	Pe_R [–]	Pe_D [–]	Pe_B [–]	Pe_{SEP} [–]	Pe_C [–]
C1	124-250	280-894	46-103	6-10	13-20
C2	71-139	85-234	16-76	3-6	5-10
C3	44-83	27-79	19-41	2-4	2-10
C4	63-144	31-115	20-37	2-11	5-7
C5	114-192	37-102	7-27	2-5	3-7
C6	47-84	20-87	27-53	3-4	8-17
C7	51-78	29-51	30-55	5-9	34-103

The results show several important implications regarding the effect of design parameters on mixing intensity. It is evident from Table 2 that the Peclet number in the riser (Pe_R) is higher than that in the downcomer for all reactor configurations with a dual separator (C3-C7, see Fig. 1). In the ALR with single enlarged head zone (C1 & C2 configurations), nil or very low gas holdup exists in the downcomer zone resulting in the increase of convection and the decrease of dispersion component in the respective Peclet number Pe_D. Lower *Pe* values in the riser were reported in the works of Lu et al. [12] and Verlaan et al. [13]. However, they measured the mixing parameters in different types of ALR: an internal-loop ALR without enlarged separator and an external-loop ALR, respectively. The Peclet numbers at the bottom part (Pe_B) were for all studied cases lower than in both riser and downcomer. The lowest Peclet numbers were found in the separator zone indicating a well-mixed reactor section. The effect of the liquid level in the head zone H_T (C3, C6 & C7 configurations) on the mixing parameters *Pe* and D_Z was not evident in riser, downcomer and bottom sections. However, a decreasing *Pe* number and increasing D_Z coefficient for both the separator and the whole reactor with increasing H_T was clearly observed, showing the highest mixing intensity in the ALR with the liquid level in enlarged zone (C3 set). This agrees with findings of Merchuk and Yunger [14], who concluded that the longer the residence time in the separator, the more intensive the mixing.

The effect of the height of the draft tube (H_{DT}/H_C) on mixing was more pronounced: the maximum mixing intensity was reached in all sections of the ALR with dual separator (C3 configuration) indicated by the lowest Pe and the highest D_Z values. The experiments with different A_D/A_R ratios confirmed that the intensity of mixing decrease with the A_D/A_R value in both riser and downcomer sections. On the contrary, the mixing in the bottom part improved with increasing area ratio due to increasing flow contraction at bottom turn. The coefficient D_Z was found to increase with air flow rate in all reactor sections reaching the maximum at the highest values of U_{Gc} equal to around 0.06 m.s^{-1}.

Optimal ALR design

To summarize the effect of design parameters on the ALR hydrodynamics: if the velocity of the liquid circulation is the major priority, an ALR with liquid level in the enlarged part of the head zone (C1-C5 configurations), an area ratio A_D/A_R around 1.7 and the draft tube with its top edge in the enlarged head zone should be used. If the total gas holdup is considered to be the most important hydrodynamic parameter, an ALR with liquid level in the narrow part of the column (C7 configuration) should be applied. The A_D/A_R ratio optimised on the base of the overall gas holdup considering riser, downcomer as well as separator zones depends on air flow rate. For $U_{Gc} < 0.03$ m.s^{-1}, the A_D/A_R equal to about 1.2 and for $U_{GRc} > 0.03$ m.s^{-1} the A_D/A_R equal to about 4.0 will be the best option to reach the highest gas content in the whole reactor. From the point of mixing intensity, the best option of the design of ALR with enlarged separator (e.g. for applications in three-phase systems) is the use of a reactor configuration with dual separator (e.g. one of the C1-C5 ALR configurations) and lower area ratio A_D/A_R (around 1.2).

CONCLUSION

The measuring tagging technique using the flowfollower allowed the acquisition of important information on the multiphase flow and distribution of gas and solid phases in the ALR. The hydrodynamics of the ALR was found to be affected by all design parameters. The impact of the change of the liquid level in the separator zone on the ALR hydrodynamics is based mainly on its effect on holdup in downcomer. The change of H_T does not significantly change average circulation velocity in the main ALR loop; however, it affects the residence time of the tagged particle in the enlarged head zone and thus its overall circulation time.

The results of experiments with different heights of draft tube demonstrated how easily various operating flow patterns can be achieved ranging from typical flow patterns for an internal-loop ALR with high downcomer gas holdup to those of an external-loop ALR with low or nil gas holdup.

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