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Behaviour of dual gas-liquid separator in an internal-loop airlift reactor – effect of top clearance

Ondrej DOLGOŠ[a], Jaroslav KLEIN[b], Antonio A. VICENTE[b] and José A. TEIXEIRA[b]

[a]*Dept. of Chemical & Biochemical Engineering, Faculty of Chemical Technology*
Slovak University of Technology, Radlinského 9, 812 37 Bratislava, Slovakia
[b]*Department of Biological Engineering, University of Minho,*
Campus of Gualtar, 4710-057 Braga, Portugal
e-mail: dolgos@chtf.stuba.sk

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1. INTRODUCTION

Airlift reactors have become increasingly interesting for use in a variety of two- and three-phase (bio)chemical processes. It is mainly because of their attractive features – a simple construction, sufficient oxygen transfer rates and intensity of mixing at low shear stresses with low energy requirement. Airlift reactors are mostly considered to consist of four parts, namely the riser, downcomer, the separator and the bottom connection. To describe the operation of the reactor, a set of parameters (liquid circulation velocity, gas holdup and bubble size distribution, mass transfer and mixing intensity etc.) in each section needs to be known. The majority of published work dealing with airlift geometry has been devoted to global reactor parameters (ALR type, height of column, column height to diameter ratio, H/D) and to its main parts – the riser and the downcomer (particularly the ratio of their cross-sectional area – A_D/A_R). Considerable less attention was paid to the influence of the separator on the ALR operation despite the fact that this section can represent a significant liquid volume of reactor. This is especially valid in a case of ALR with an enlarged head zone. Few papers [1-5] showed that the design of the gas separator can have a substantial effect on the transport phenomena in the ALR. The main purpose of the head region of airlift reactors, where the riser and the downcomer interconnect, is the gas disengagement. This effect is usually achieved by increasing the cross-sectional area of the reactor head zone, where the reduce of a velocity of liquid flowing downwards into the downcomer occurs. Only few papers have presented studies in internal-loop airlift reactor with a significantly enlarged head zone, e.g. [6-9]. None of them was concerned with three-phase flow. However, the enlarged separator can acts as an efficient sedimentation region for continuous three-phase ALR (e.g. immobilised or flocculating systems), where a separation of a solid phase from the gas-liquid dispersion is of a particular importance [10].
Generally, the gas-liquid separator affects the difference in gas holdup between the riser and downcomer – the driving force for liquid circulation and an extent of bubble recirculation and thus, consequently affects all hydrodynamic and mass transfer characteristic of airlift reactors. An interesting study about the influence of the separator design on the operation of rectangular ALRs was done by Siegel et al. [2]. The authors observed not only a significant influence of the separator design (shape, size but also the liquid level in the separator H_T) on the hydrodynamic parameters of the reactor (liquid velocity V_L, gas holdup ε_G), but also that the influence of pressure drop was lower than the influence of the separation ability of the separator. In ALRs of various sizes but with similar separators the values of liquid circulation velocity were very similar. Merchuk et al. [3] in line with Siegel [2] observed that a change of the separator design markedly influenced the oxygen transfer rate. In a further work Siegel et al.[1] showed that if the size of the separator (diameter, other dimensions) is lower than a critical value, then its size has a significant influence on hydrodynamic conditions in ALRs. Above this critical size the liquid level in the separator H_T will have the decisive influence. During measurements performed in a rectangular ALR he observed a further interesting phenomenon: by diminishing the part of the separator on the side of the riser the

extent of bubble separation was not reduced. That means that – in terms of bubble separation – the part of the separator on the side of the riser represents a dead volume. In contradiction with the opinions of Siegel et al.[2] and Merchuk et al.[3], Chisti et al.[4], Russel et al.[11], Lu et al.[12] and others did not observe a significant effect of the liquid height in the separator H_T on the liquid circulation and the gas holdup. According to them, H_T would have a certain influence only in the case of its low value. Russel et al.[11] observed the existence of two zones in the separator, where the liquid passed predominantly through the lower part. When the level of liquid exceeded this zone, the gas holdup in the downcomer as well as the circulation velocity did not change any more (at constant air flow rate). Thus, it can be concluded that H_T does not have a significant influence on V_L and ε_G, although there are published contradictory opinions [2, 3]. The most plausible suggestion is unless the size of the gas separator (diameter) is greater than the critical value, its size has a dominant influence on ε_{GD} and gas recirculation [1]. When the size of the separator increases above the critical value, the liquid level H_T will play a key role in the extent of penetration of bubbles into the downcomer.

The main goal of this study was to investigate the influence of liquid height in the enlarged head zone on the hydrodynamics in a 60 L internal-loop airlift bioreactor. Particularly, the hydrodynamic study was focused on the behaviour of the separator acting as the degassing and sedimentation zone in airlift reactor, which was designing for three-phase flow purposes.

2. MATERIALS AND METHODS

2.1. The reactor set-up

Measurements of liquid circulation velocity and gas holdup were performed in a 60 L concentric draught tube airlift bioreactor with an enlarged degassing zone (see Fig. 1). The basic dimensions of reactor are listed in Table 1.

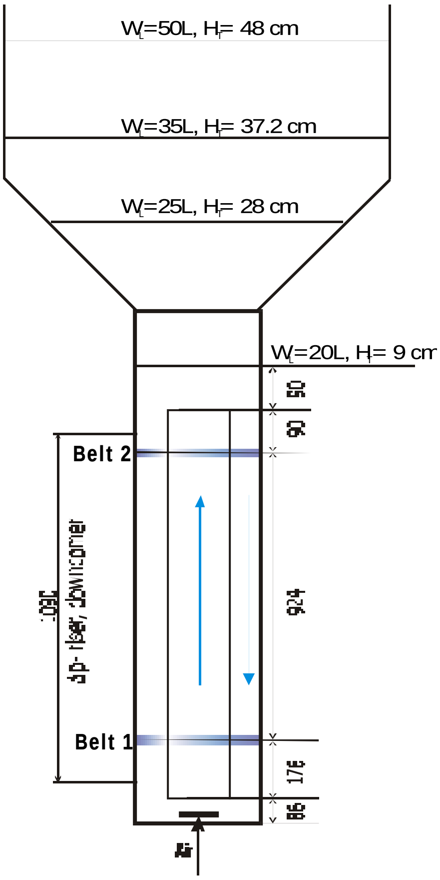

Fig. 1. Scheme of airlift reactor with indication of different liquid heights applied.

Table 1: Basic characteristics of ALR used in experiments.
D_c *– column diameter,* D_R *– riser tube diameter,* A_R *– riser cross-sectional area,* A_D *– downcomer cross-sectional area,* H_{DT} *– height of the draft tube,* D_S *– diameter of separator zone,* H_S *– height of separator zone.*

D_C [mm]	H_C [m]	D_R [mm]	A_D/A_R [-]	H_{DT} [m]	D_S [m]	H_S [m]
142/158	1.986	62/70	3.97	1.190	0.442	0.350

The head section is of the cylindrical conical type. The conical section forms a 51° angle with the main body of the reactor. The working volumes of the reactor were 20 l, 25 l, 35 l and 50 l. In all experiments water and air were used as the liquid and gas phase, respectively. The experiments were carried out at an average temperature of 19 ° C and atmospheric pressure. The air injection was made 0.061 m below the bottom of the draft tube by means of acircular plate with adiameter of 0.03 m, with 30 holes of 1 mm each one. The air flow rate was controlled by means of rotameters. In the results the air flow is given as the characteristic riser superficial velocity, U_{GRC}. This parameter was calculated according to the air flow rate for the conditions in the geometric centre of the column.

2.2. Measurements of hydrodynamic parameters

A magnetic tracer method [13] was used to determine important hydrodynamic parameters in the internal-loop ALR. The method makes use of the principle of a magnetic metal locator and flowfollowing. A magnetic particle with a high magnetic permeability and diameter of 1 cm was used as the flowfollower. The particle density was adjusted almost exactly to the liquid density, which resulted in very low terminal settling velocity (up to 1 cm/s). The measuring technique allow to determine liquid circulation velocities and residence times of tagging particle in individual sections of the airlift reactor.

2.3. Measurement of the gas holdup

The gas holdup was determined by the manometric method. Inverted water manometers were used for the measurement of pressure differences between two places in the riser and downcomer of the ALR. The positions of measuring points were properly chosen in order to avoid the effect of an liquid acceleration at the bottom and the top of the draught tube [3]. Then, the average overall gas holdups, $\boldsymbol{e}_{GR}$ and $\boldsymbol{e}_{GD}$, were calculated, as in e.g. [14].

3. RESULTS AND DISCUSSION

In terms of the shape of the top of the airlift reactors can be classified as follows – airlift reactors without a separator (the separator diameter is equal to the diameter of the outer column) and with a separator (the separator diameter is larger than the diameter of the outer column). In this work measurements were performed in an airlift reactor with an enlarged head zone. However, it can be seen for the construction of the ALR presented that both configuartions of ALR can be considered (see Fig. 1):
1/ If both the degassing liquid level and the dispersion G-L level are below the conical enlarged part of the separator, then this system can be considered as an airlift reactor without separator.
2/ If both the degassing liquid level and the dispersion G-L level are in the conical part of the separator or in the highest head zone , then this system can be considered as an airlift reactor with separator.
In Fig.2 the dependence of V_{LD} and V_{LR} values on the superficial air velocity U_{GRC} for different heights of liquid level in the reactor head zone is depicted.

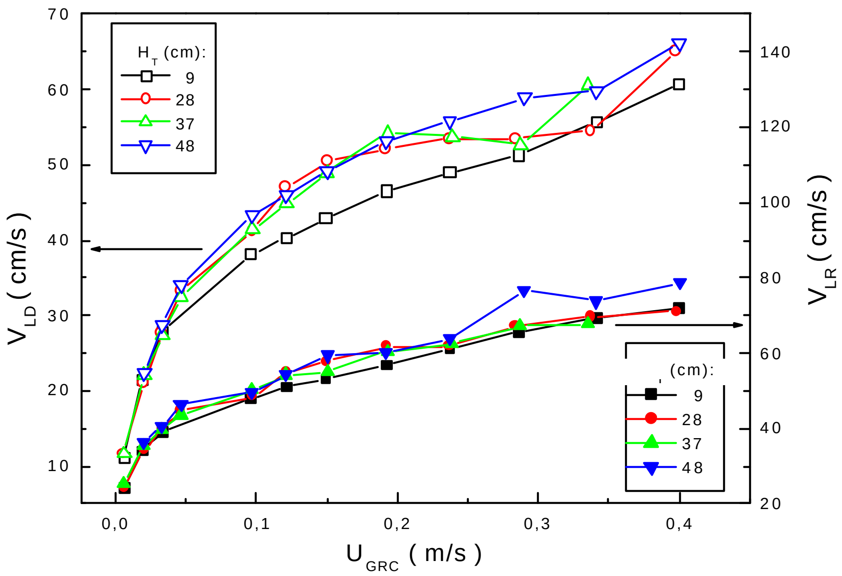

Fig.2: The linear liquid velocity in the downcomer and riser as a function of the superficial air velocity.

It can be seen, that the linear liquid velocity in the downcomer and riser increased with the height of liquid level. The courses of V_{LD} values are much less the same for all working volumes of the reactor (typical logarithmic form), but for the riser liquid velocities the situation is different.
On the V_{LR} curve three regions can be noticed: 1. region for U_{GRC} < 0,1 m.s^{-1}; 2. region for U_{GRC} = 0,1 – 0,3 m.s^{-1}; 3. region for U_{GRC} > 0,3 m.s^{-1}.
For the first region the values of V_{LR} are equal for all heights of liquid level H_T. This suggests that for U_{GRC} < 0,1 m.s^{-1} the height of level in the separator H_T does not have any influence on the liquid circulation velocity in the riser. A different situation was in the case of the second region, for which the values of V_{LR} are lower for the working volume of the reactor W_L = 20 L than for other working volumes W_L, for which is the course equal within the whole range of air flow rates.
At U_{GRC} = 0.1 m.s^{-1} bubbles began to be entrained into the downcomer and a transition regime was observed (see also Fig. 3, in which for U_{GRC} = 0.1 m.s^{-1} the gas hold up begins to rise in the downcomer). At the end of this region at U_{GRC} = 0.3 m.s^{-1} (beginning of the third region) the values of V_{LR} are again the same for all variations of H_T, because the liquid level increased from the part above the riser to the conical head zone of the reactor and the reactor started to act further as an ALR with separator. It can be concluded, that for the lowest liquid level the reactor acts as an ALR without separator with prevailing hydraulic resistance over the gas separation ability, what affects liquid circulation velocity in the riser in comparison with other cases, where the top liquid level reached the enlarged degassing zone. At higher liquid reactor volumes the liquid level did not have any significant influence on the liquid circulation velocity in the riser.

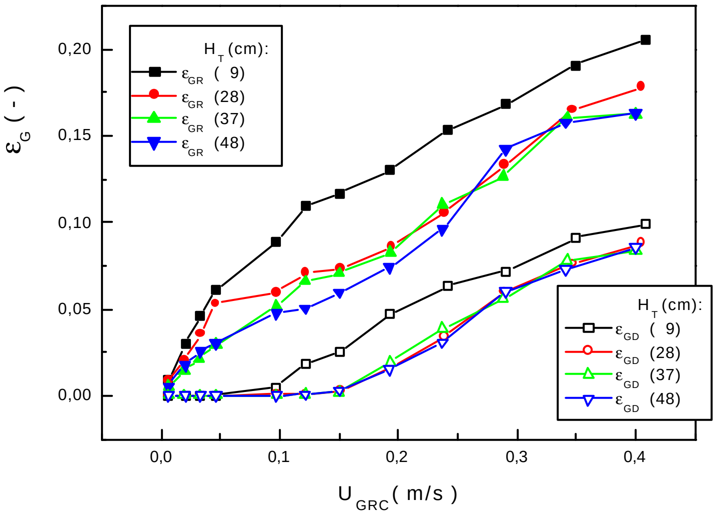

Fig.3: Effect of liquid level in the separator on the gas holup in the riser and downcomer.

Figure 3 shows the effect of the height of liquid level on the gas hold up in the riser and downcomer. It is clear that the gas holdup in the riser and downcomer increases with increasing height of liquid level in the separator. For H_T equal to 9 cm, the gas holdup in the riser and downcomer is higher for the entire operating range of U_{GRC} than for other higher values of H_T. In Fig. 2 it can be seen that V_{LR} is lower in the case of a 20 L reactor than for other working volumes. The consequence is an increase of the bubble residence time in the riser and as a result higher ε_{GR}. Higher values of ε_{GD} are given by the configuration of the separator, when more bubbles are entrained into the downcomer.

Up to the velocity U_{GRC} equals to 0,1 m.s^{-1} the gas holdup in the downcomer is zero and from this point the ε_{GD} appeared to increase what corresponded to the onset of the entrainment of bubbles into the downcomer. For higher values of W_L, the bubble penetration into the downcomer appeared at higher air flow rates ($U_{GRC} \geq 0.15$ m.s^{-1}), when the influence of the separator started manifesting because of the heights of liquid situated in the conical or enlarged parts of the separator (see Fig. 1).

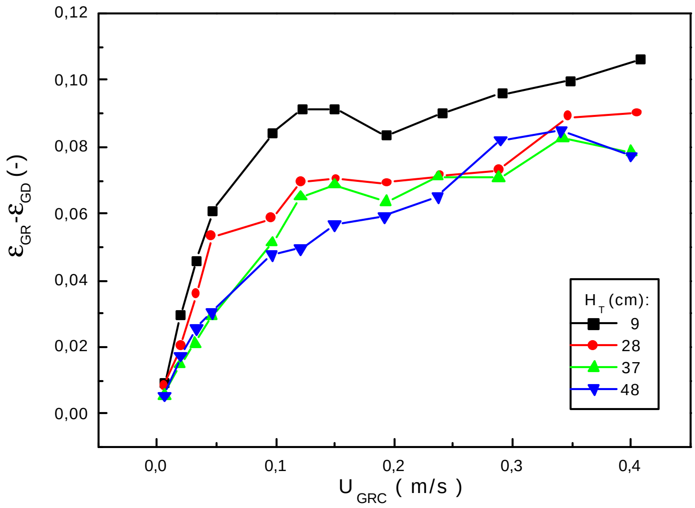

Fig. 4. Driving force of liquid circulation as a function of the U_{GRC} for different liquid levels in the separator.

Very interesting is the influence of the height of liquid level in the separator H_T on the driving force of the liquid circulation (i.e. the difference of gas holdups in the riser and downcomer), which is depicted in Fig. 4. It could be expected that the highest driving force should be for the airlift reactor with a working volume 50 L, for which the most efficient separation of bubbles in the head zone should occur. However, Fig. 4 revealed an opposite tendency. The driving force of the liquid circulation decreased with increasing W_L. This can be elucidated by the fact that the highest driving force refers to the highest losses. It is valid especially in the case of the lowest liquid level, where high liquid flow resistance dominated over the bubble separation ability.

Since the method for measuring circulation velocities enabled to study of the residence time and average velocities in all sections of the ALR, our effort could was also focused on data of residence time distribution of the tagging particle in the separator and together with visual observations to describe the character of flow of phases in the separator. In addition, we could determine the overall circulation time of liquid in the reactor.

In Fig. 4 the overall circulation times vs. air superficial velocity is depicted.

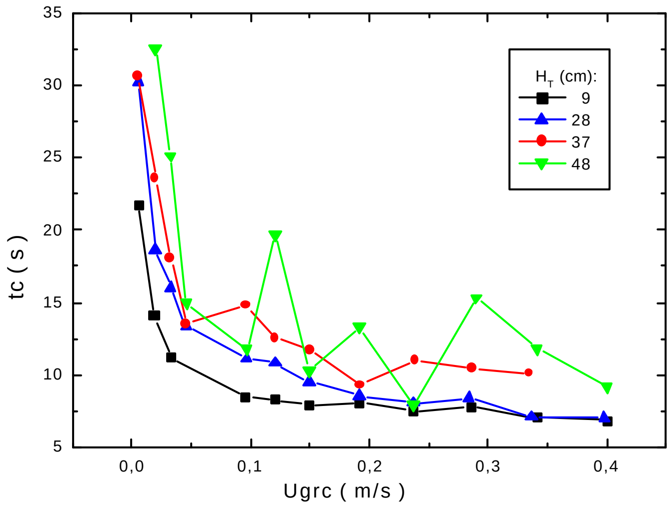

Fig. 5. Circulation time as a function of air superficial velocity for different values of H_T.

From this Figure one can see that the lowest values of t_c are for H_T = 9 cm and with increasing H_T the overall circulation time increased. For the highest H_T equal to 48 cm the course of the plot is much scattered. This is mainly caused by occasional very high residence times of the particle in the upper part of the separator.

In Figs. 5a, 5b and 5c histograms of residence time distribution of the tagging particle in the separator for various working volumes of the reactor is drawn. On the basis of these graphs and visual observations one can consider three flow patterns of the particle in the separator, which are schematically shown in Fig. 6.

Flow pattern A: The particle is entrained by the prevailing liquid flow directly into the downcomer. This corresponds to the highest number of residence times of the particle (about 5-10 s). This regime can be observed mainly in an ALR with a working volume of 20 L, in which the liquid level is closely above the riser and for other working volume at low air superficial velocities.

Flow pattern B: The turbulent region is formed closely under the top of the graft tube in the lower part of the separator, especially for higher air flow rates. There an intensive mixing of liquid takes place. According to visual observations, the particle sometimes reached this zone and was entrained by eddies and after a short circulating in this zone was entrained back into the downcomer without reaching the enlarged zone. This resulted in higher residence times of the particle (in average about 10-20 s).

Flow pattern C: The tagging particle is entrained up to the upper part of the separator, where it is hold for a longer time and then it is drawn along the wall into the downcomer. The consequence of this are pretty high residence times for the particle (above 30 s). This regime can be found especially in the case of the working volume W_L = 50 L and in a small extent for working volumes of 25 and 35 L.

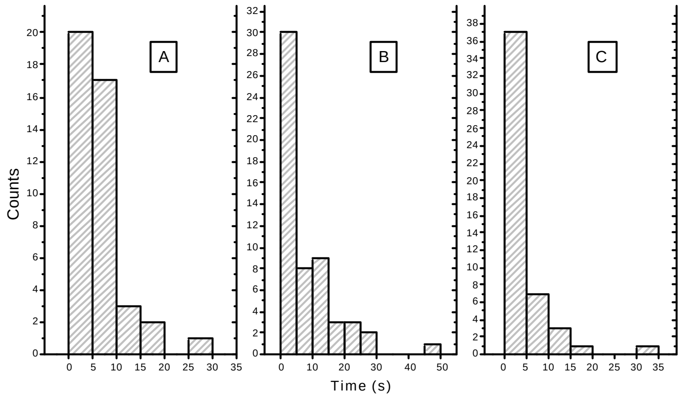

Fig. 5a. W_L = 25 L, U_{GRC} ($m.s^{-1}$): A. 0.046, B. 0.121, C. 0.238

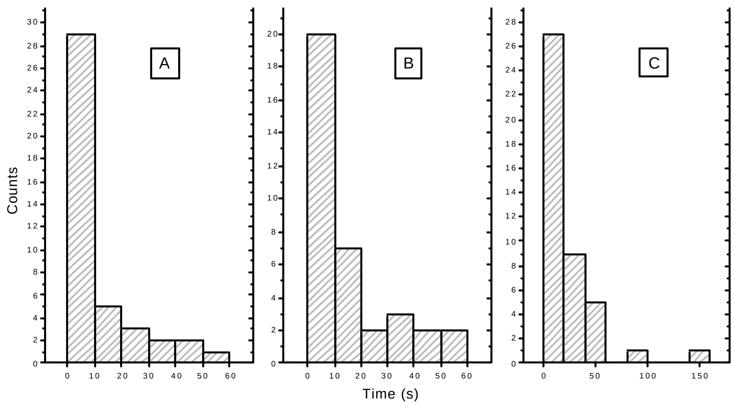

Fig. 5b. W_L = 35 L U_{GRC} ($m.s^{-1}$): A. 0.046, B. 0.121, C. 0.238

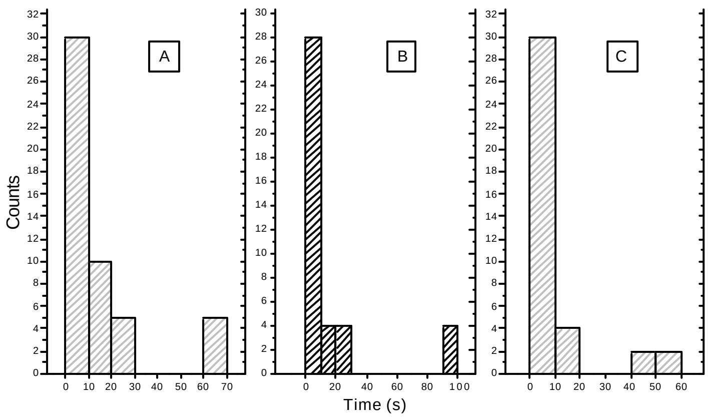

Fig. 5c. W_L = 50 L U_{GRC} ($m.s^{-1}$): A. 0.046, B. 0.121, C. 0.238

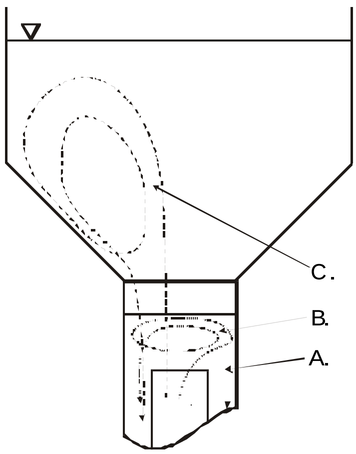

Fig. 6. Flow pattern in the separator

According to these histograms, the separation of values of resisdence times of the tagging particle in the separator corresponding to the direct 180° turn of particle from the riser to downcomer, was done. These t_c values could adequately mimic the values measured using pulse response methods. The Fig. 7 depicts these adapted circulation times and shows its independence on the variation of liquid level in the separator. This suggests that these scatters of t_c values are mainly caused by the fluctuations of the liquid flow in the separator.

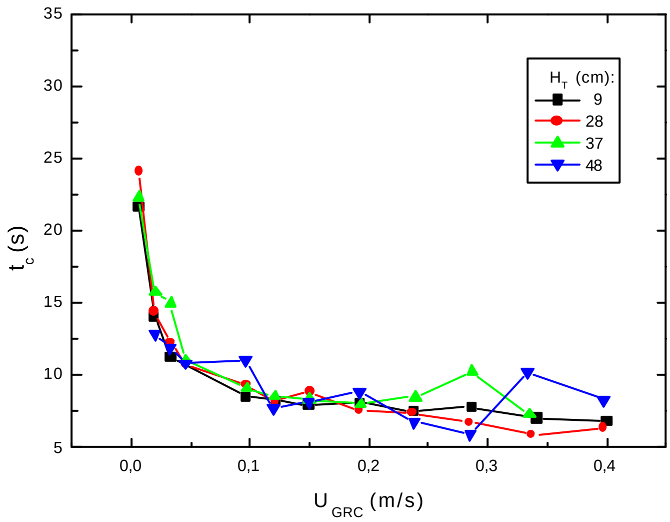

Fig. 7. Adapted values of circulation times for various liquid levels in the separator.

4. CONCLUSION

A difference in gas holdups between main vertical sections of an airlift reactor (ALR) – the riser and the downcomer provides the driving force for liquid circulation, which in turn affects all the hydrodynamics, transport phenomena and mixing in the ALR. Therefore, the performance characteristics of the airlift reactor are strongly affected by the bubble disengagement in the head zone acting as a gas-liquid separator. This study was devoted to the measurement of global hydrodynamic characteristics (gas hold-up and liquid circulating velocity) of the internal loop airlift reactor with an enlarged degassing zone and the investigation of the behaviour of a dual gas-liquid separator at different heights of liquid in the separator. The working volume of the reactor used in this work was 20 L, 25 L, 35 L and 50 L, which corespond to the distance between the upper edge of the draft tube and the top level of liquid of 9, 28, 37.2 and 48 cm, respectively.

It was shown that for the lowest liquid level the reactor acts as an ALR without separator with prevailing hydraulic resistance over the gas separation ability, what strongly affects all important hydrodynamic parameters in comparison with other cases, where the top liquid level reached the enlarged degassing zone. At higher liquid reactor volumes the liquid level did not have any significant influence on the reactor hydrodynamics any more. Moreover, the histograms of residence times of tagging particle in the head enlarged zone revealed interesting facts related to its acting as a gas-liquid separator as well as sedimentation zone.

Acknowledgments

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