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HYDRODYNAMICS OF A SELF-AGITATED DRAFT TUBE AIRLIFT REACTOR

Article Highlights

- A novel-constructed draft tube airlift reactor, self-agitated by ten impellers, was investigated
- The insertion of impellers caused bubble breakup and reduction of mean bubble size
- The riser gas holdup increases while the downcomer almost diminishes, bringing to lower overall gas holdup
- Circulation time is prolonged, downcomer liquid velocity decreases and mixing time increases
- Constructed reactor shows better performance compared to previous studies with other internals

Abstract

The main hydrodynamic characteristics of a novel-constructed, self-agitated draft tube airlift reactor (DT-ALR) were investigated. Ten impellers, driven only by means of gas throughput and induced liquid circulation, were inserted in the draft tube. The insertion of impellers caused bubble breakup and reduction of both mean bubble size and coalescence, even under the conditions of high gas throughputs. Although the impellers induced energy losses, the resistance to the flow was relatively lower due to their rotation, unlike the internals used in other research reported in the literature. In comparison to the conventional configuration of a DT-ALR, it was found that the presence of impellers led to significant changes in hydrodynamics: riser gas holdup and mixing time increased, while overall gas holdup and liquid velocity in the downcomer decreased.

Keywords: draft-tube airlift reactor, internals, self-agitated impellers, hydrodynamics.

Airlift reactors (ALRs) have important applications in chemical and biochemical processes, due to numerous advantages they offer as efficient and economical devices for enabling an intimate interfacial contact in different gas-liquid and gas-liquid-solid operations. The main aim to enhance the bubble breakup, but also to intensify the mass transfer in these reactors, led to intensive research of different reactor designs. Some of the solutions were to introduce a kind of an internal “obstacle”, which would alter the hydrodynamics and mass transfer in the investigated contactors. Table 1 summarizes the research to date in this matter.

Lin *et al.* [1] studied the performance of an external loop airlift reactor (EL-ALR) with slanted baffles placed on the riser wall, facing downwards at an angle of 30°. Although the mixing and the circulation time were drastically prolonged with the incorporated baffles, the mass transfer was improved, leading to increased product yields in such fermentors.

Different packing materials can be used as catalysts or biomass carriers in ALRs. Placed in the riser section, packing induces change in the flow patterns in comparison to the unpacked reactor, leading to greater flow tortuosity, longer path lengths for bubbles to travel and therefore, intensified interaction between the bubbles and the packing material [2,3]. Gopal and Sharma [2] investigated the influence of Pall rings in the riser of a draft tube airlift reactor (DT-ALR). Although such packing increased the resistance to the liquid flow, decreasing the liquid circulation velocity and disabling the bubble penetration in

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Table 1. Review of studies in airlift reactors with internals

Reference	Reactor type and charateristics	Internal	Investigated parameters
Lin et al. (1976)	EL-ALR; D_R = 0.15 m, D_D = 0.05 m, H = 3 m	Slanted baffles	k_La, t_m, t_c
Gopal and Sharma (1982)	DT-ALR; D = 0.2 m, D_{DT} = 0.11 m, H_{DT} = 0.96 m	16 mm Stainless steell Pall rings	W_{LD}, W_{LR}, ε_G, ε_{GR}, a, k_La, k_L, Δp
Meng et al. (2002)	EL-ALR; D_R = 0.089 m, D_D = 0.047 m, H_R = 1.81 m	Woven nylon packing	ε_G, W_L, axial dispersion, bubble size distribution
Stejskal and Potůček (1985)	DT-ALR; D = 0.11 m, D_{DT} = 0.058 m	Kenics-180° static mixer	k_La, N_G, ε_G, ε_{GD}
Gaspillo and Goto (1991)	slurry DT-ALR; D = 0.097 m, D_{DT} = 0.027 m, H = 0.37 m	Static mixer	Δp, $U_{G,min}$, k_La
Goto and Gaspillo (1992)	Slurry EL-ALR; D_R = 0.027 m, D_D = 0.061 m, H_R = 0.585 m, H_D = 0.39 m	Static mixer	Δp, U_{LR}, $U_{G,min}$, k_La
Chisti et al. (1990)	EL-ALR; D_R = 0.050 m, D_D = 0.075 m	SMV-12 Static mixer elements	k_La
Gavrilescu et al. (1997)	EL-ALR; A_D/A_R = 0.1225	Sulzer type static mixer	W_L, ε_{GR}
Zhao et al. (1994)	DT-ALR; D = 0.14 m, D_{DT} = 0.09 m, H = 1.7 m	Baffle caps, sieve plates	k_La, ε_G, W_L
Vorapongsathorn et al. (2001)	DT-ALR; D = 0.137 m, D_{DT} = 0.093 m, H_{DT} = 1 m	3 Perforated baffle plates	ε_G, ε_{GD}, ε_{GR}, k_La, W_L
Krichnavaruk and Pavasant (2002)	DT-ALR; D = 0.098 m, D_{DT} = 0.068 m, H = 2.4 m, H_{DT} = 2.07 m	Perforated plates	W_{LD}, k_La, ε_{GR}
Chisti and Jauregui-Haza (2002)	DT-ALR annulus sparged; D = 0.755 m, D_{DT} = 0.50 m, H = 3.21 m, H_{DT} = 2.06 m	2 Impellers mechanically agitated	k_La, ε_G

the downcomer, the increase in the interfacial area (a) by a factor of 3-5 was observed. The research of Meng *et al.* [3], conducted in an external loop airlift bioreactor (EL-ALR) packed with woven nylon in the riser section, showed that optimal hydrodynamic conditions occurred at high packing porosity with the full packing height. Such conditions permitted high holdup of immobilized biomass attached to the packing, highest gas holdup to improve the mass transfer and large void space to reduce plugging and liquid frictional losses.

Breakup of the bubbles in the ALRs can be achieved with static mixers. Stejskal and Potůček [4] reported that Kenics static mixers in the draft tube enhanced the origination of very fine gas bubbles, which recirculated through the column. The bubbles were held in the draft tube longer, but the downcomer gas holdup was lower in the presence of the motionless mixer, because of lower liquid velocity. Gaspillo and Goto [5,6] investigated the influence of a static mixer in a riser of slurry DT-ALR and EL-ALR. In their research, static mixers were effective in dispersion of large bubbles created by a single nozzle. On the other hand, when a different distributor (which created very fine bubbles) was used, the presence of static mixer induced coalescence [5,6]. The research of Gavrilescu *et al.* [7], conducted in an EL-ALR with Sulzer static mixers in the riser, showed that in the non-Newtonian solutions the riser gas holdup was significantly increased. However, the liquid circulation superficial velocity in the riser section was diminished, due to a decrease in downcomer to riser cross-section ratio in the presence of the motionless mixer. The presence of static mixer led to an increase in mass transfer coefficient in both water-like [5,6,8] and non-Newtonian media [4,8].

Insertion of perforated plates could also modify the gas phase dispersion. Zhao *et al.* [9] studied the influence of baffles in several design modes of bubble columns (BCs) and DT-ALRs filled with Newtonian and non-Newtonian liquids. Two types of baffles were used: a baffle cap, formed by mounting a perforated plate on top of a short tube, and a perforated plate. Placed in the draft tube of a DT-ALR, the baffles caused an accumulation of bubbles underneath. When the pressure drop across the orifice of the perforated plate was overcome, the gas was redistributed. Therefore, the gas was bubbled periodically through the baffles and the liquid circulation velocity was decreased. Mass transfer was enhanced with introduction of baffles in all reactor types with viscous Newtonian liquids. Nevertheless, the effect of baffles was less pronounced in case of non-Newtonian liquids. Complete investigations of hydrodynamics and mass transfer in a DT-ALR with three perforated plates in the draft tube were performed by Vorapongsathorn *et al.* [10]. The research showed that presence of baffles reduced liquid circulation velocity, as they obstructed flow and increased the resistance to the liquid flow. Also, the baffles reduced the bubble rise velocity, thus leading to a slight enhancement of the riser holdup in comparison to the non-baffled configuration. Downcomer gas holdup was decreased by lowering the liquid velocity. The result was a negligible effect of baffles on the overall gas holdup, and related volumetric mass transfer coefficient. The presence of baffles led to a development of stagnant regions underneath the plates, which streamlined the flow path. This phenomenon resulted in the rise of liquid velocity with the increase of the power throughput. Exhaustive analysis of the perforated plate effect on bubble forming or breakage in a DT-ALR was presented by Krichnavaruk and Pavasant [11]. By employing a photographical technique, a very studious analysis on this phenomenon was performed in several reactor designs with various plate number and plate configurations. The role of the perforated plate was to break large bubbles into smaller ones. However, it was observed that they coalesced again after they left perforated plate and gained almost equal size as before they reached the plate. Plates with too large free area were less effective in bubble breakage. The presence of plates reduced riser liquid velocity and circulation velocity, but augmented riser gas holdup and interfacial mass transfer area (a). Although the mass transfer coefficient (k_L) was decreased, the overall volumetric mass transfer coefficient was as much as twice the value obtained from the conventional DT-ALR.

Improved agitation in the DT-ALR was evaluated through research of Chisti and Jauregui-Haza [12]. Two low-power hydrofoil impellers, mechanically driven by a motor, were used to enhance fluid circulation in the reactor. The gas was sparged into the annular zone to avoid the impeller flooding. It was found that the gas holdup rose with increasing aeration and agitation rates. The effect of mechanical agitation on mixing time was pronounced at relatively low aeration rates. At higher aeration velocities, rising bubbles were the dominant cause of the mixing. The oxygen transfer capability was improved, but the oxygen transfer efficiency was reduced by use of mechanical agitation. Generally, the authors concluded that the use of mentioned impellers in the downcomer of an ALR could substantially enhance the rate of liquid circulation, mixing and gas-liquid mass transfer relative to operation without the agitator. However, the performance improvement was made through disproportionate increase in the power consumption [12].

Investigations of the DT-ALR with different type of internals in the draft tube have shown that these contactors are mainly superior to the conventional configuration. Insertion of internals, such as baffles, static mixers or packing increases the gas holdup, breaks up the bubbles, and therefore, enhances the mass transfer by increasing the specific interfacial area (a). However, these internals increased the resistance to the liquid flow. Thus, the liquid velocity is lower and the pressure drop is significantly higher. In such conditions the volumetric mass transfer coefficient (k_La) might be decreased.

It is known that addition of a separator can also alter the hydrodynamics in a DT-ALR [13]. This kind of modification leads to lower downcomer gas holdup, in comparison to configuration without the separator. In this case, the investment costs are probably significantly lower than in reactors with different baffles, static mixers or other internals. However, the presence of the separator affects the separation of the gas phase at the top, therefore on the driving force for the liquid circulation, but has no additional influence on the bubble breakup. Although additional parts such as baffles, packing, static mixers, *etc.* (see Table 1) bring further costs and lead to a more complex construction of reactors, generally known as simple-constructed, they have their specific role as biomass carriers, turbulence promoters, *etc.*

As it can be seen from Table 1, previous research of modified reactors included only the configurations with packing, static baffles, perforated plates or static mixers. Until now, reactors with incurporated impellers were mechanically agitated. The objective of this experimental work was to introduce agitation in the DT-ALR using the already present energy of the gas throughput. So, the hydrodynamics of a self-agitated DT-ALR, as a novel-constructed contactor, with inserted impellers in the riser section was investigated and compared to the conventional DT-ALR. In this initial stage of our research only a single orifice (known as the least effective sparger) was used as the gas distributor, in order to point out the strong impact of the impellers on bubble breakup and additional mixing. The impellers were rotated by the gas throughput and induced liquid circulation; therefore, the resistance should be lower in comparison to motionless internals.

EXPERIMENTAL SETUP

The experiments were performed at 20±1 °C and atmospheric pressure in a glass DT-ALR, with geometrical details presented in Figure 1. Two configurations of the same reactor were used: conventional DT-ALR and a configuration with impellers installed in the riser. A shaft with 10 impellers was

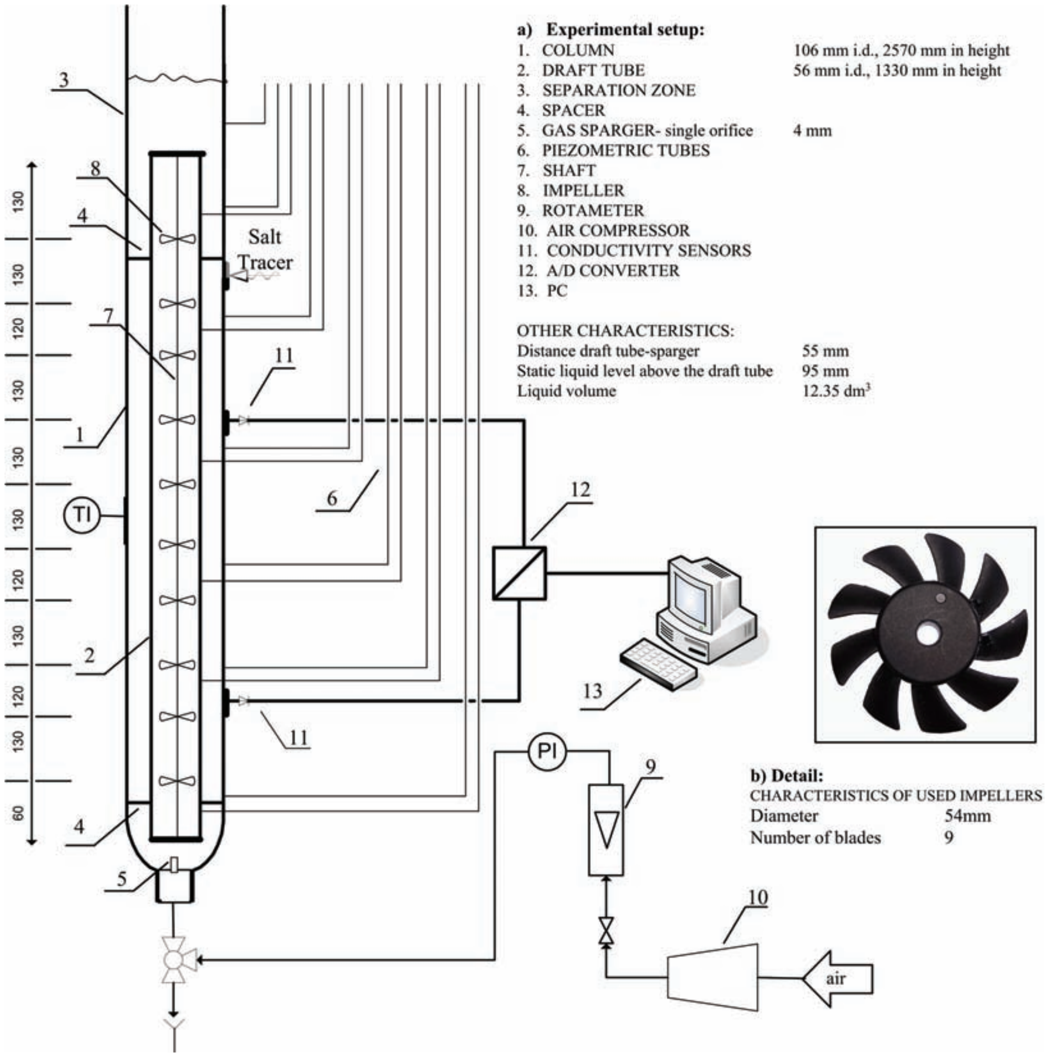

Figure 1. Experimental setup.

mounted in the centre of the draft tube. In order to reduce the friction between the impellers and the shaft, Teflon rings were placed in the plastic impeller's shell. The impellers were driven only by the gas throughput and induced liquid circulation. The distance between the impellers and their geometrical details are depicted in Figure 1. The number and disposition of the impellers were chosen based on a preliminary research, in order to achieve the best performance: breakup of the bubbles with the minimum resistance to the flow. It was noticed that all the impellers started rotating simultaneously at the lowest gas flow used in this experimental work (Q_G = 200 l/h). This minimum gas flow was chosen having in mind that the obtained gas holdup in this case overcomes the error of the employed experimental method.

The air, sparged through a single orifice into the draft tube, was used as the gas phase. The gas flow rates were controlled and measured by a rotameter. Tap water was used as the liquid phase.

The overall gas holdup was determined by the volume expansion technique with an error less than 10%. The gas holdup values along the downcomer were obtained by measuring the pressures at five points using piezometric tubes. In order to reduce the liquid surface fluctuations in the piezometric tubes, the capillaries (50 mm in length and 0.7 mm i.d.) were inserted at the entrance of the tubes. Therefore, the relative average error of these measurements was diminished to 2%. Values of the gas holdup in the separator were also determined by piezometric tube placed at the entrance of the separator. The riser gas holdup was calculated upon the balance equation:

$$\varepsilon_{GR} = \frac{H_{GL}(A_D + A_R)\varepsilon_G - H_{DT}A_D\varepsilon_{GD} - (H_{GL} - H_{DT})(A_D + A_R)\varepsilon_{GS}}{H_{DT}A_R} \tag{1}$$

Downcomer liquid velocity, liquid circulation time and the mixing time were measured by a pulse tracer technique. Two self-constructed conductivity sensors were placed in the downcomer section (as it is shown in Figure 1) at L = 0.75 m distance from each other. Solution of 4 mol/l NaCl, used as a tracer, was injected in the downcomer (Figure 1). The signal, caused by the tracer pass between the sensors, was measured using an A/D converter and recorded on a PC as a conductivity-time function with characteristic peaks. Measurements were performed with a sampling frequency of 0.2 s until no change was observed in the liquid phase conductivity. The moment when the tracer was registered by the sensor (t_1 for the first and t_2 for the second sensor), later used as an output value, was obtained as half peak width at base. The time delay between the signals of both sensors was used for calculation of liquid velocity based on the following equation:

$$W_{LD} = \frac{L}{(t_2 - t_1)} \qquad (2)$$

For each value of a gas flow rate, at least five measurements were performed and the average value of downcomer interstitial liquid velocity was calculated. The relative average error of this method was ±5%.

Liquid circulation time (t_c) was determined with the relative average error of ±5% from the same measurements, as the time difference between the two adjacent peaks on the output signals for both sensors.

Mixing time (t_m) was calculated from the output signal for the first sensor, as the time required for the decrease of output signal to 5% of the maximum signal value. The relative average error of the measurements was ±10%.

The impeller rotation was recorded on a Samsung VP-D353i camera. One of the blades on the impeller was marked with vivid yellow color. Therefore, the impeller speed was later calculated by tracking the marked blade through several rotations by analyzing the video sequences.

RESULTS AND DISCUSSION

Hydrodynamics - main observations and the influence of impellers. Visually, it was observed that all the impellers in the modified DT-ALR started rotation under the minimal gas throughput employed in this experimental work. The rotation speed was almost uniform regardless to the impeller position along the riser. As it can be seen from Figure 2a, the impellers speed increased with the increase of the superficial gas velocity. At low gas throughputs this increase is very high, according to the slope of the function impellers speed vs. superficial gas velocity. However, as the observed transition between the regimes in the riser occurred, the increase in the impellers speed became less steep (see Figure 2a). In the turbulent regime, the backward liquid flow probably hindered the impellers rotation. Therefore, above the superficial gas velocities of 0.05 m/s, the impellers rotation speed tended to be constant.

Pressure of the gas entering the column was measured in order to quantify the resistance of impellers. As it is obvious from Figure 2b, no major increase in the pressure value was noticed, in comparison to the reactor without the impellers, until $U_G \approx$ ≈ 0.050 m/s, which corresponds to the slug flow in the riser. On the contrary, it seems that the impeller's rotation streamlined the flow, thus lowering the expected resistance. From that point ($U_G \approx 0.050$ m/s) forward, the resistance to the gas throughput was larger in the presence of impellers because of the intensified circulation of bubbles and detention of the gas in the riser. Also, the energy necessary for the impeller rotation was increased, as the riser was filled with gas plugs. All of this resulted in about 17% higher pressure of gas at the inlet in the self-agitated reactor.

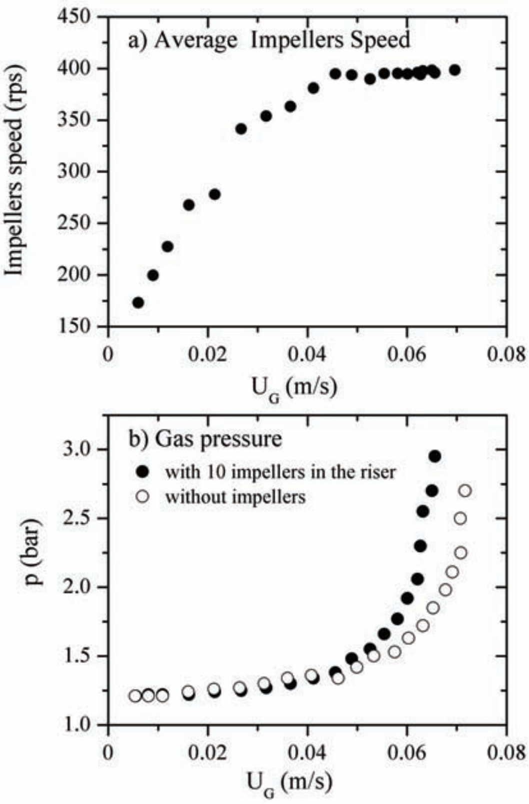

Figure 2. Average impellers speed and pressure of gas entering the column as a function of superficial gas velocity.

Insertion of impellers in the draft tube of the DT-ALR led to significant changes in the hydrodynamics, in comparison to the conventional configuration. Rotation of the impellers caused breakup of the large bubbles originated in the draft tube and contributed to a uniform radial distribution of the bubbles, for lower superficial gas velocities. The bubble coalescence in the draft tube was reduced, in comparison to the conventional DT-ALR. Although the impellers could be observed as obstacles to the gas upflow in the riser, neither the accumulation of bubbles nor the formation of air pockets under the impellers were noticed. Intensive bubble breakup enabled origination of many, very small, bubbles (< 1 mm in diameter) that were dragged into the downcomer. At low gas throughput, these bubbles accumulated at the entrance of the downcomer, forming a kind of resistive layer. With an increase of the gas superficial velocity, this resistance to the liquid circulation was overcome, and the bubbles started recirculating. However, in the presence of the impellers, even under high gas throughputs, the downcomer was filled with tiny bubbles of 1-2 mm in diameter and less, because of which the downcomer bulk was milky. The rise velocity of such small bubbles was very low; therefore, they are detained in the column for a few minutes even if the gas flow was stopped. Also, the impellers enhanced the lagging of bubbles. In the modified configuration of the ALR, even under the conditions of the slug flow in the riser ($U_G \approx 0.050$ m/s), the bubbles in the downcomer were smaller in diameter and much more stable to the tendency of coalescence, in comparison to the conventional reactor. The coalescence occurred only at the entrance in the annulus, but at much higher gas throughputs than in the conventional DT-ALR. Although the bubbles of larger diameters (4-6 mm) were present in the downcomer at superficial gas velocities of about 0.053 m/s, they formed a stagnant layer. Through their accumulation a certain zone was created, whose boundary with the underneath region of small bubbles was sharp. As the superficial gas velocity rose, the zone of larger bubbles was moving downward the annulus, until they started recirculating at superficial gas velocities of about 0.062 m/s. From this point forward, the number of larger, stable bubbles in the downcomer increased noticeably.

Gas holdup. Figure 3 illustrates the comparison of the overall, riser and downcomer gas holdup between the two airlift configurations - with and without the impellers. Presence of the impellers induced significant increase in the riser gas holdup, which became even higher with an increase of the gas throughput. By the following: breaking up the bubbles, reducing their coalescence and prolonging detention of bubbles in the riser, the gas holdup in the draft tube became 80-200% (mainly about 100%) larger, in comparison to the conventional reactor. Also, the appearance of the very large air bubbles, which fill out almost the whole cross section of the riser, was prolonged and attenuated. On the other hand, the presence of very small bubbles in the downcomer resulted in a very low downcomer gas holdup, which, in a self-agitated ALR, did not exceed the value of 2% unless a significant increase of the gas throughput took place. The reduction of the downcomer gas holdup in the reactor with incorporated impellers was about 88%, in comparison to the reactor without impellers. As the result of simultaneous enlargement of the riser holdup and extreme reduc-

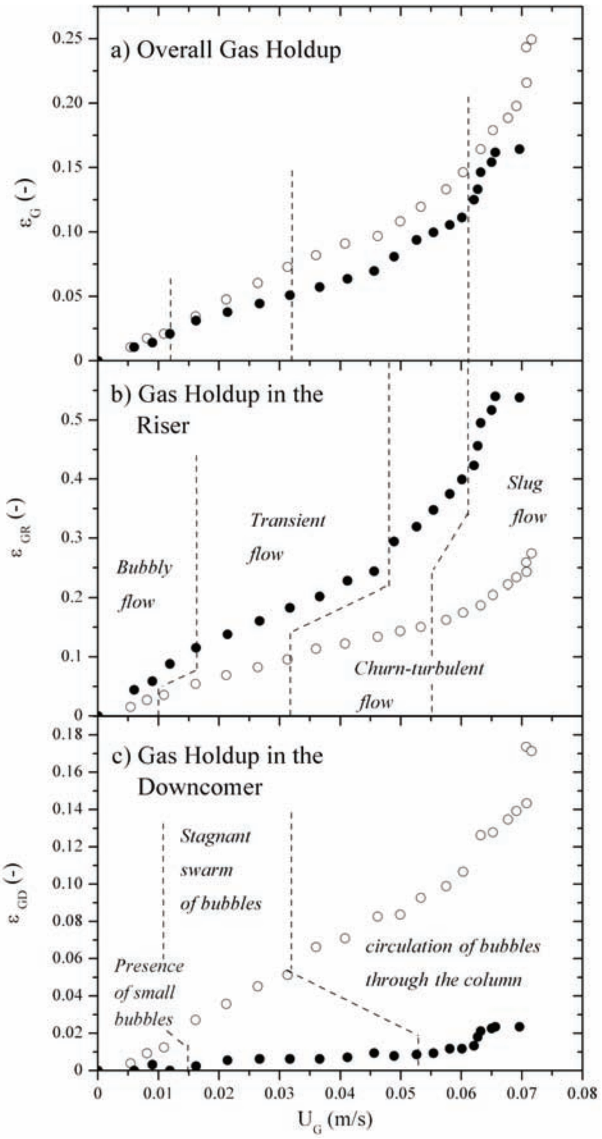

Figure 3. Overall, riser and downcomer gas holdup as a function of superficial gas velocity and reactor configuration.

tion of the downcomer gas holdup, the overall gas holdup in the novel DT-ALR was either equal to the gas holdup in the conventional DT-ALR or about 24% lower. Obviously, for this reactor geometry, it is expected that the changes in the downcomer gas holdup have dominant influence on the overall gas holdup.

Based on the research of Blažej *et al.* [14], higher downcomer, riser and overall gas holdups and higher liquid circulation velocity could be obtained in reactors of larger scale. In larger reactors, different specific friction against liquid circulation exists in comparison to smaller reactors. Also, the gas phase in larger reactors recirculated even in the case of the lowest values of the superficial gas velocity. Having in mind that reactor scale strongly affects the hydrodynamics [14], research with added impellers should also be conducted in larger reactors, in order to examine the results from the small-scale reactor used in this work.

Liquid phase velocity and circulation time. The difference between the riser and the downcomer holdup, as the driving force for the liquid circulation through the column, is presented in Figure 4, as a function of the superficial gas velocity for both reactor with and reactor without the impellers. The disproportional increase in the riser holdup and decrease in the downcomer gas holdup led to significant enhancement of the driving force of about 370% in the modified reactor configuration. It is to be expected that this enlarged driving force will increase the liquid circulation velocity. However, the circulation time was about 1.9 times higher (see Figure 4b), thus the liquid circulation velocity was lower, if the impellers were present. The reason could be found in energy losses due to maintaining the impellers rotation, but also in extended flow path and flow tortuosity. Also, the decrease in the circulation time with an increase in superficial gas velocity was more pronounced in the reactor with added impellers. The dampening of the circulation velocity led to an entrainment of only tiny bubbles in the downcomer. As the bubble breakup by the impellers enhanced the origination of very small bubbles (< 1 mm), they hoarded at the downcomer entrance and formed a resistive layer for liquid circulation. Therefore, the downcomer liquid velocity was about 2.2 times lower in the DT-ALR with impellers (Figure 4c). By entrainment of larger bubbles into the downcomer and after their accumulation at the upper part of this region, for higher superficial gas velocities, the hydraulic resistance to the liquid flow increased causing the descent in liquid velocity. It can be noticed that the downcomer liquid velocity tended to settle at almost constant value, despite the increase of gas throughput.

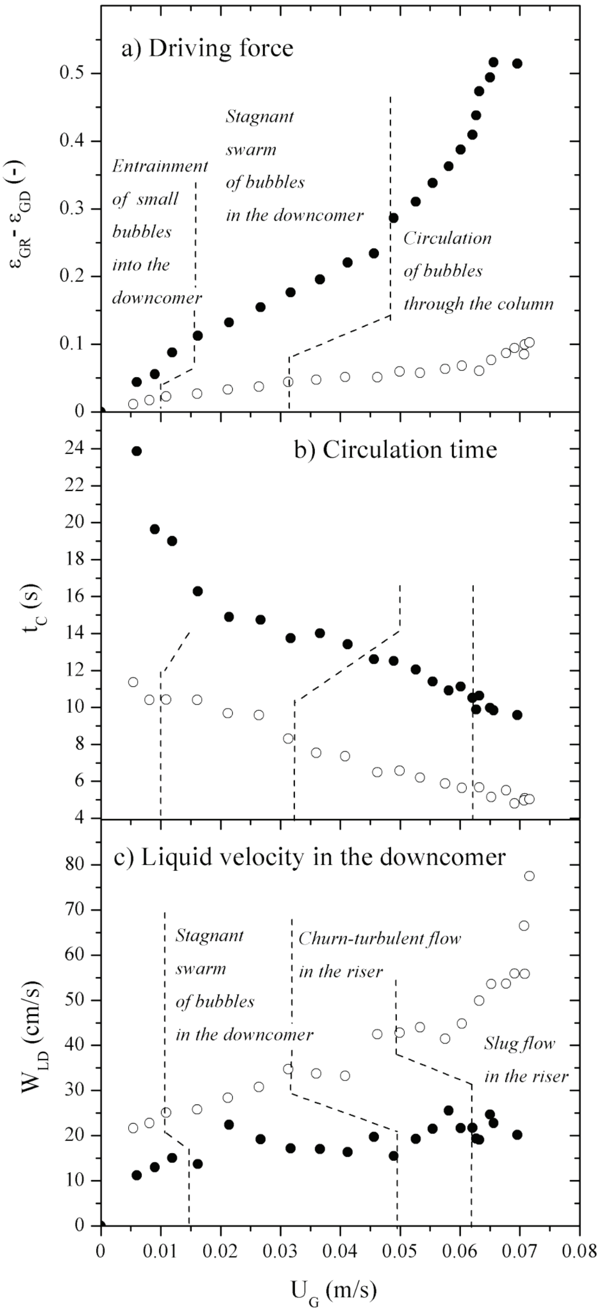

Figure 4. Driving force, circulation time and downcomer liquid velocity as a function of superficial gas velocity and reactor configuration.

The transition between the following regimes in the downcomer: 1) presence of small bubbles, 2) formation of stagnant swarm of bubbles and 3) circulation of bubbles through the column, could be observed in Figures 3 and 4, for both reactors, as the changes in the slopes of the curves representing the overall gas holdup, driving force and downcomer liquid velocity. The transition between the named regimes shifts to higher gas throughputs in the presence of impellers, as indicated by the dashed lines in the mentioned figures.

Mixing time. The influence of superficial gas velocity in both reactor with and reactor without impellers on mixing time is depicted in Figure 5. For both reactor configurations, the mixing time decreased with increased gas throughput. Insertion of impellers in the draft tube deteriorated the mixing performances. In the self-agitated reactor, three characteristic peaks (see Figure 5), showing local minima of the mixing time function, could be observed for superficial gas velocities of about 0.032, 0.050 and 0.063 m/s. The mentioned velocities correspond to the visually observed transition moments when the increased liquid velocity was sufficient enough to enable the recirculation of the accrued larger bubbles in the downcomer. Growing presence of bubbles and their circulation was an important factor for mixing improvement. Similar observations, meaning that flow regimes and the presence of solids or internals could alter the hydrodynamics and, therefore, have strong influence on the mixing time, are found in other papers [15,16]. Pandit and Joshi [15] reported that mixing phenomenon in gas-liquid contactors depends upon the gross liquid circulation and the microscale turbulence, while the molecular diffusion is usually negligible. They also concluded that introduction of the draft tube in the BC reduced the turbulence in annulus and enhanced the clear circulation pattern, thus increasing the mixing time in comparison to the BC. Petrović *et al*. [16] investigated the mixing in the gas-liquid-solid DT-ALR, but the similar observations in the mixing time were reported as in this paper. The flow regime of bubbles had great influence on the mixing and circulation time. Bubble entrainment in the annulus led to less intensive mixing as the stationary cloud of bubbles presented the hydraulic resistance to the flow. As the stationary cloud of bubbles was formed, the mixing time versus superficial gas velocity curve shows the local minima. When this resistance was overcome and the circulation of bubbles through the column started, the mixing time decreased and the local maxima on the mixing time curve appeared. Chisti and Jauregui-Haza [12] also confirmed that the movement of bubbles through the contactor is the dominant cause of mixing.

Blažej *et al.* [14] concluded that the increase in reactor scale provided higher circulation velocities and shorter mixing times, but also a better distribution of the gas phase. Therefore, it is to be expected that the use of impellers in reactor of larger scale could lead to better performance in sense of mixing.

Comparison of results obtained in this work with the results of previous experiments is presented in Figure 6. Figure 6a depicts the overall gas holdup in reactors with different types of internals [2,4,8,10] along with the values obtained in this experimental work. The differences between the mentioned values,

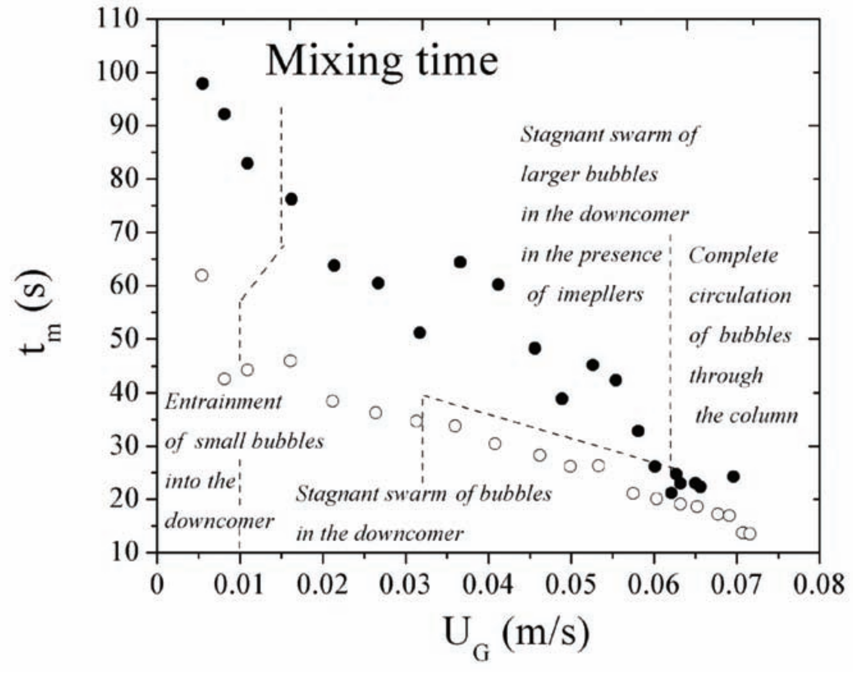

Figure 5. Mixing time as a function of superficial gas velocity and reactor configuration. Legend: ○ reactor without impellers, ● reactor with 10 impellers in the riser.

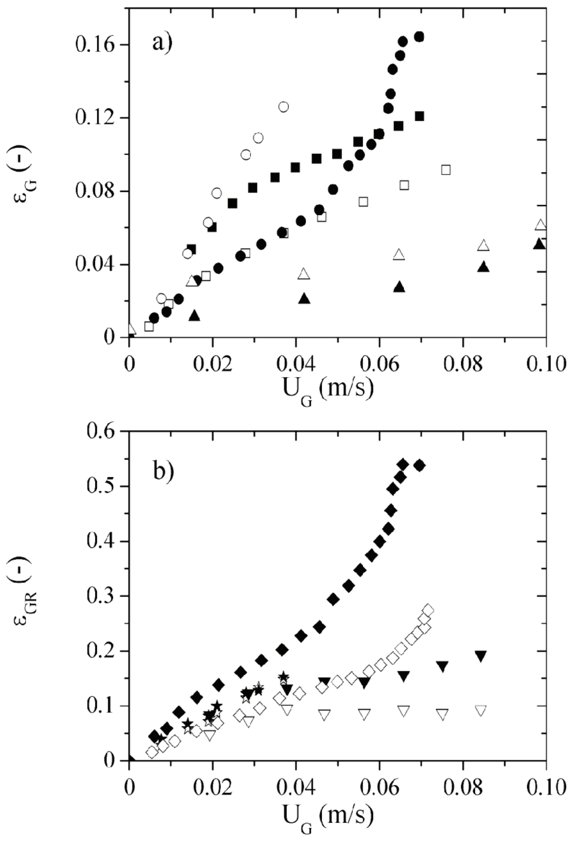

Figure 6. Comparison of previous research with this study. a) Influence of internals on the overall gas holdup; Legend: ■ Gopal and Sharma [2] (reactor with Pall rings), □ Stejskal and Potůček [4] (reactor with Kencis static mixers), ● this study (reactor with impellers), ○ Vorapongsathorn et al. [10] (reactor with perforated baffle plates), ▲ Chisti and Jauregui-Haza [12] (reactor without mechanical agitation by impellers), Δ Chisti and Jauregui-Haza [12] (reactor with mechanical agitation, impeller speed 170 rpm)). b) Riser gas holdup comparison of previous research with this study; Legend: □ Vorapongsathorn et al. [10] (reactor without baffles), ■ Vorapongsathorn et al. [10] (reactor with baffles), Δ Krichnavaruk and Pavasant [11] (reactor without perforated plates), ▲ Krichnavaruk and Pavasant [11] (reactor with perforated plates), ○ this study (reactor without impellers), ● this study (reactor with impellers).

besides the insert type, could be associated mainly with different reactor geometry, as well as type of used gas sparger. Stejskal and Potůček [4] conducted experiments in a DT-ALR with riser to column diameter ratio (D_R/D) equal to the ratio in our work. Before reaching $U_G \approx 0.05$ m/s, the values of the overall ε_G, in both cases, were similar. Later, for higher superficial gas velocities our experimental ε_G values were 25–48% higher, which led to the conclusion that the impellers provided better gas dispersion than static mixers, even with less effective gas distributor. The values for overall gas holdup, reported by Gopal and Sharma [2], are about 50% higher than ours, for all U_G values less than 0.06 m/s. After that, we obtained about 25% higher values, owing to the advantages of impellers in comparison to the packing. Our results are about 100% lower than the ones of Vorapongsathorn *et al.* [10], probably because they employed a shorter draft tube and a reactor with higher D_R/D ratio. However, in comparison to Chisti and Jauregui-Haza [12], who introduced agitation by mechanically driven impellers, our results are about 200% higher. Having in mind that the column used in their experimental work was of much larger scale, the results are not completely quantitatively comparable with ours.

In the case of the riser gas holdup, our results show enhancement of about 100% after insertion of impellers. Figure 6b presents the results of other authors [10,11] in comparison to the results of this experimental work. In both cases [10,11], the enhancement in riser gas holdup is lower. Vorapongsathorn *et al.* [10] found that, in comparison to the conventional reactor, the inserted perforated baffle plates increased the riser gas holdup for about 15%, but Krichnavaruk and Pavasant [11] reported the increase of about 73% with the same internals. Nevertheless, comparison of riser gas holdup values from Figure 6b shows that our results are about 25–45% higher than the results of others [10,11] because of our modification.

CONCLUSIONS

The results of the presented work show that the insertion of impellers in the riser section of a DT-ALR strongly alters its hydrodynamics. In comparison to the conventional DT-ALR, the following effects are noticed:

- The gas holdup in the riser noticeably increases, but the downcomer gas holdup almost diminishes, resulting in slightly lower overall gas holdup.
- Circulation time is prolonged and the downcomer liquid velocity decreases.
- Mixing time increases, thus, the overall mixing is not enhanced due to presence of impellers.
- The results show that the obtained riser gas holdup values in this experimental work, especially under the conditions of higher gas throughputs, are much higher in comparison to previous experimental studies with other internals. Also, the appearance of the slug flow in the riser was prolonged, thus leading to more stable reactor operation.

Therefore, better understanding of the impellers effect on the hydrodynamics and mass transfer of self-agitated DT-ALR requires future research that would allow application of various liquids as well as measurements of mass transfer coefficients on the novel-constructed and other similar reactors.

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Nomenclature

A	cross sectional area (m^2)
D	diameter of column (m)
D_R	inner diameter of riser (m)
D_D	inner diameter of downcomer (m)
k_La	volumetric mass transfer coefficient (1/s)
L	distance between the conductivity sensors (m)
H	height (m)
N_G	gas power output (W)
Δp	pressure drop (bar)
t_c	liquid circulation time (s)
t_m	mixing time (s)
t	time (s)
U_G	superficial gas velocity, column based (m/s)
W_{LD}	downcomer interstitial liquid velocity (m/s)

Abbreviations

ALR	airlift reactor
BC	bubble column
DT-ALR	draft tube airlift reactor
EL-ALR	external loop airlift reactor
rps	rotations per second

Greek letters

ε_G	gas holdup

Subscripts

C	circulation
D	downcomer
DT	draft tube
G	gas phase
L	liquid phase
R	riser
S	separation zone

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NAUČNI RAD

HIDRODINAMIKA SAMO-MEŠAJUĆE BARBOTAŽNE KOLONE SA KONCENTRIČNOM CEVI

U ovom radu su istražene glavne hidrodinamičke karakteristike novog tipa barbotažne kolone sa koncentričnom cevi, sa samo-pokretajućim impelerima. U centralnoj cevi kolone bilo je postavljeno deset impelera koji su bili pokretani isključivo pomoću uvođenja gasa u kolonu i usled toga, indukovane cirkulacije tečnosti. Prisustvo impelera je uzrokovalo razbijanje mehurova, smanjenje njihove veličine kao i redukciju koalescencije, čak i pri velikim brzinama gasa. Mada su impeleri uzrokovali dodatne gubitke energije, otpor proticanju tečnosti je bio relativno mali, zbog njihovog okretanja, u poređenju sa podacima drugih autora dostupnih u literaturi, koji su koristili druge umetke U poređenju sa uobičajenom konfiguracijom barbotažne kolone sa koncentričnom cevi, primećeno je da je prisustvo impelera uzrokovalo značajne hidrodinamičke promene: sadržaj gasa u centralnoj cevi i vreme mešanja su povećani, dok su ukupan sadržaj gasa i brzina tečnosti u anulusu smanjeni.

Ključne reči: barbotažna kolona sa koncentričnom cevi, umetci, samo-pokretajući impeleri, hidrodinamika