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Hydrodynamics of two- and three-phase systems in an agitated vessel with two agitators

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The effect of the agitators configuration, the agitator speed, the volumetric gas flow rate, the sucrose concentration in aqueous solution, and the yeast suspension concentration on the hydrodynamics of two- or three-phase systems in an agitated vessel with two agitators has been presented in this paper. The gas hold-up and the average residence time of the bubbles were measured in agitated vessel with a liquid height of H = $2D$ and the internal diameter of D = 0.288 m. The study was carried out for gas-liquid and biophase-gas-liquid systems, where the gas phase was air, the liquid phase was distilled water or an aqueous solution of sucrose (c = 2.5% mass., 5% mass.), and the biophase was a suspension of Saccharomyces cerevisiae yeast (y_s = 1% mass.). The research results were analysed taking into account the influence of the type of the upper or lower agitator, agitator speed, gas flow rate, and type of liquid in the system on the gas hold-up and the average residence time of the gas bubbles. The experimental results were mathematically described.

Keywords: agitated vessel, gas hold-up, residence time of gas bubbles, gas-liquid or biophase-gas-liquid.

INTRODUCTION

Mixing of multiphase systems is used in many industries, e.g. chemical, food, biotechnological, or pharmaceutical to obtain the homogeneity of the mixture and the stability of the parameters of the manufactured systems[1, 2]. Mixing can be done in different ways, e.g. using different agitators or agitator configurations. In tanks with one or more agitators, the hydrodynamics of the system can be determined by determining various quantities[3–9]. In the case when one of the phases is the gas phase, the parameters characterizing the hydrodynamics of such systems are the gas hold-up or the average residence time of gas bubbles in the agitated vessel[10–14]. Knowledge of these quantities is very important, especially in the case of biological systems in which providing the appropriate amount of oxygen to the liquid is necessary to maintain the appropriate biological balance and the proper metabolism of the microorganisms (organisms) occurring there. In addition to providing enough oxygen, you also need to know how long this amount of oxygen will remain in the liquid. Because oxygen will not remain in the water for too long, the liquid should be aerated so that oxygen losses are continuously supplemented[15–19].

Obtaining appropriate working conditions is possible with the proper selection of geometric, physical, and operational parameters. Unfortunately, it is not possible to determine the influence of these parameters on the hydrodynamic state of such a system. Research should take into account not only the impact of individual parameters but also the relationships between these parameters[4, 14, 20–22]. For example, by analysing the influence of selected parameters, it can be clearly stated that with an increase in the agitator speed, assuming a constant value of the volumetric gas flow rate, both the gas hold-up and the average residence time of gas bubbles increase, and with an increase in the volumetric flow rate gas, assuming a constant value of the agitator speed, the gas hold-up increases and the residence time of gas bubbles decreases. However, how much the individual quantities increase or decrease depends on the other parameters included in the given system.

In the literature, you can find papers in which the authors analysed the influence of operational parameters[3, 5, 16, 18, 21, 23, 24] (agitator speed, volumetric gas flow rate), physical parameters[10, 16, 24–28] (density and viscosity of individual phases, the concentration of individual phases, surface tension), geometric parameters of the agitated vessel[14, 21, 23, 24, 29–31] (vessel diameter, the height of liquid, presence or absence of baffles, number of baffles, etc), geometric parameters of the agitator[14, 21,23, 32–38] (type of agitator, the diameter of the agitator, number of agitator blades, inclination or curvature of the agitator blades, etc) on the hydrodynamics of multiphase systems.

One of the basic criteria for maintaining the proper hydrodynamic state in the agitated vessel is the appropriate selection of the configuration of the agitators on one shaft. In the case of vessels with a height of the liquid greater than the diameter of the vessel, more agitators are mounted on the agitator shaft. To obtain good working conditions with the lowest possible energy expenditure, the number of agitators, their type and proper placement of individual agitators on the shaft should be selected properly[3, 23, 24, 27, 33].

The study presented in this paper is aimed at determining the influence of the agitators configurations, the agitator speed, the gas flow rate, the sucrose concentration in aqueous solution, and the yeast suspension concentration on the hydrodynamics of two- or three-phase systems in an agitated vessel with two agitators.

MATERIALS AND METHODS

The gas hold-up and the average residence time were measured in agitated vessel with a liquid height of $H = 2D$ and an internal diameter of D = 0.288 m. Five different agitators configurations lower (L) – upper (U) high-speed agitators were used in the measurements: $RT_{(L)}$-$RT_{(U)}$, $RT_{(L)}$-$CD6_{(U)}$, $RT_{(L)}$-$HE3_{(U)}$, $CD6_{(L)}$-$RT_{(U)}$, $CD6_{(L)}$-$HE3_{(U)}$. The tests were carried out in an agitated vessel with a liquid height of H = 2D, therefore it was necessary to install two agitators on the shaft. Additionally, in the case of multiphase systems, it is necessary to select agitators in such a way as to achieve both good dispersion of gas bubbles and suspension of solid particles (biophase) in the entire volume of the agitated vessel. Based on the results available in the literature, it can be concluded that the most advantageous agitator configuration, allowing to obtain the highest values of the gas hold-up, is the configuration consisting of two Rushton turbine agitators. Unfortunately, this configuration has its drawbacks: firstly, Rushton agitators are classified as a group of agitators characterized by high (or even very high) energy consumption[39] – the power number for a single Rushton turbine agitator is about 5, for two about 11, secondly, they are characterized by high shear stresses, which is not advantageous, especially for systems with a biological phase. To find a system that would allow for obtaining similar values of the gas hold-up, with lower energy input and lower shear stresses, various agitator configurations were used in the research, in which agitators with modified shapes were installed as the upper, lower or upper and lower ones. The results of the gas hold up and the average residence time effects obtained for the above configurations were compared with the results obtained for the configurations of the A $315_{(L)}$-$RT_{(U)}$, A $315_{(L)}$-CD $6_{(U)}$, A $315_{(L)}$-$HE_{(U)}$, $RT_{(L)}$-A$315_{(U)}$, CD $6_{(L)}$-A $315_{(U)}$, discussed in detail in the paper Major and Cudak[24]. Detailed parameters of the agitated vessel and agitators are shown in Figure 1 and in Tables 1 and 2.

Table 1. Geometrical parameters of agitated vessel

No.	Geometrical parameters of agitated vessel	Parameter values
1.	Inner vessel diameter	$D = 0.288$ m
2.	Liquid height in vessel	$H = 2D$
3.	Number of baffles	$J = 4$
4.	Width of the baffle	$B = 0.1D$
5.	Number of agitators	$i = 2$
6.	The distance of the lower agitator from the bottom	$h_1 = 0.17\ H$
7.	The distance of the upper agitator from the bottom	$h_2 = 0.67\ H$
7.	Gas sparger off-bottom clearance	$e = 0.5h$
8.	Gas sparger diameter	$d_d = 0.7D$

The study was carried out for gas-liquid and biophase-gas-liquid systems, where the gas phase was air (V_g, $m^3/s \in <2.22 \times 10^{-4}; 5.56 \times 10^{-4}>$), the liquid phase was distilled water ($c = 0\%$ mass.) or an aqueous solution of sucrose ($c = 2.5\%$ mass., 5% mass.), and the biophase was a suspension of *Saccharomyces cerevisiae* yeast ($c = 5\%$ mass., $y_s = 1\%$ mass.).

The physical properties of the analysed system changed in the following ranges: surface tension σ [N/m] $\in <0.072; 0.086>$; density ϱ [kg/m^3] $\in <1000; 1019>$, dynamic viscosity coefficient of the liquid phase η_L [Pas] $\in <1 \times 10^{-3}; 1,12 \times 10^{-3}>$; dynamic viscosity coefficient for the biophase-liquid system (($c = 5\%$ mass., $y_s = 1\%$ mass.) was calculated from the following equation:

$$\eta_{b-L} = K \cdot \gamma^{m-1} \qquad (1)$$

where the consistency constant $K = 0.0052$; flow index $m = 0.829$.

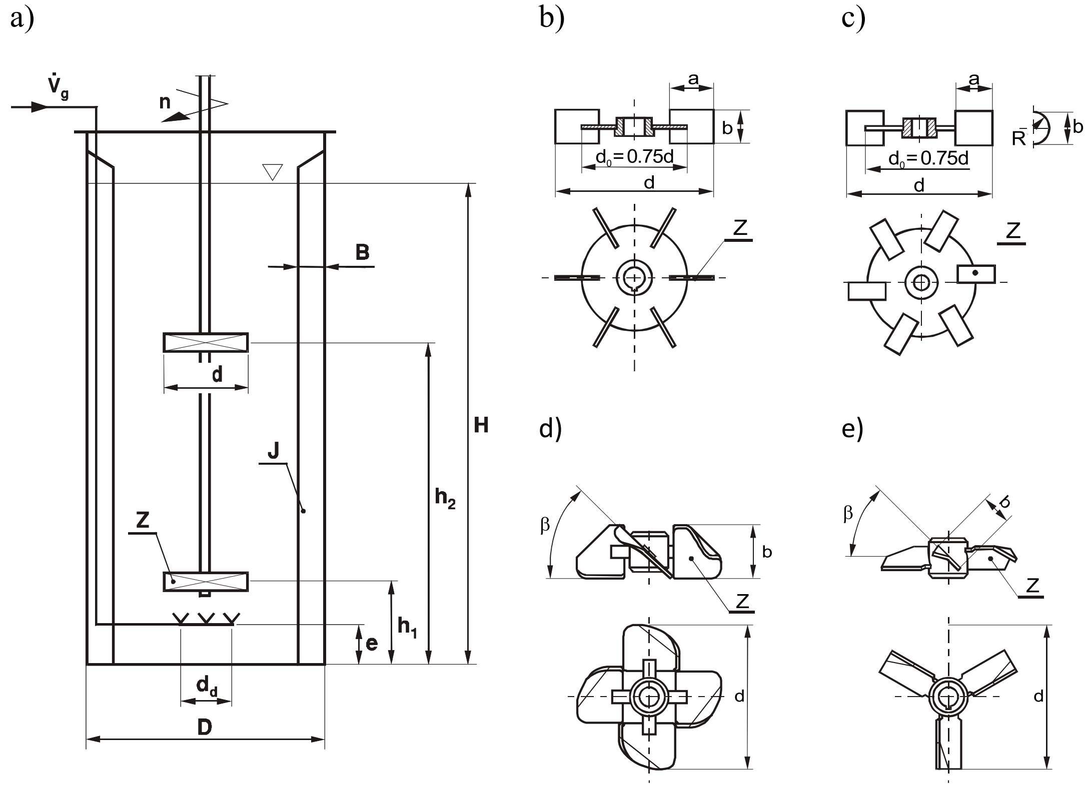

Figure 1. Geometrical parameters of the: a) agitated vessel; b) Rushton turbine agitator (RT); c) Smith turbine agitator (CD6); d) A 315 agitator; e) HE3 agitator

Table 2. Geometrical parameters of agitators

No.	Agitator	*d/D*	*a/d*	*b/d*	*Z*	*β*
1.	Rushton turbine (RT)	0.33	0.25	0.2	6	–
2.	Smith turbine (CD6)	0.33	0.25	0.2	6	–
3.	A 315	0.33	–	0.34	4	45
4.	HE3	0.33	–	0.2	3	30

The gas hold-up φ and the average residence time t_R of gas bubbles were calculated, from equations

$$\varphi = \frac{h}{h+H} \tag{2}$$

$$t_R = \frac{V_L \varphi}{V_g(1-\varphi)} \tag{3}$$

RESULTS AND DISCUSSION

The analysis of the effect of the agitators configurations, the agitator speed, the volumetric gas flow rate, the sucrose concentration in aqueous solution, and the yeast suspension concentration on the hydrodynamics of two- or three-phase systems in an agitated vessel with two agitators was performed based on about 5800 measurement points.

The results of the research on the influence of different parameters on the gas hold-up are shown in Figures 2–5. In all analysed cases, the gas hold-up increased with the increase in the agitator speed and with the increase in the volumetric gas flow rate. Depending on the configuration of the agitators, increasing the agitator speed, e.g. from 10 1/s to 12 1/s, resulted in an increase in the gas hold-up by about 10–30% (Fig. 2). The influence of the agitator speed on the gas hold-up practically did not depend on the volumetric gas flow rate and the type of liquid in the system. The influence of the volumetric gas flow rate on the gas hold-up depended on the configuration of the agitators and the type of liquid in the system. In the case of the system with distilled water, the increase in the volumetric gas flow rate V_g = 2.22 x 10^{-4} m^3/s to V_g = 5.56 x 10^{-4} m^3/s resulted in an increase in the gas hold-up from 1.5 to 2.5 times (Fig. 2). The greatest influence of the volumetric gas flow rate on the gas hold-up was found for the configuration of the agitators in which the CD6 agitator was installed as the bottom one. Adding sucrose to the system reduced the effect of the volumetric gas flow rate on the gas hold-up. In the case of systems with an aqueous solution of sucrose with a concentration of 5% by mass. increasing V_g = 2.22 x 10^{-4} m^3/s to V_g = 5.56 x 10^{-4} m^3/s resulted in an increase in the gas hold-up by about 30–70% (depending on the agitators configuration). In turn, the addition of yeast to the system caused the gas hold-up to increase by about 60–90% with the increase in the volumetric gas flow rate (from V_g = 2.22 x 10^{-4} m^3/s to V_g = 5.56 x 10^{-4} m^3/s) (Fig. 2).

The influence of the agitator configuration on the gas hold-up is shown in Figures 3–4. Based on the obtained

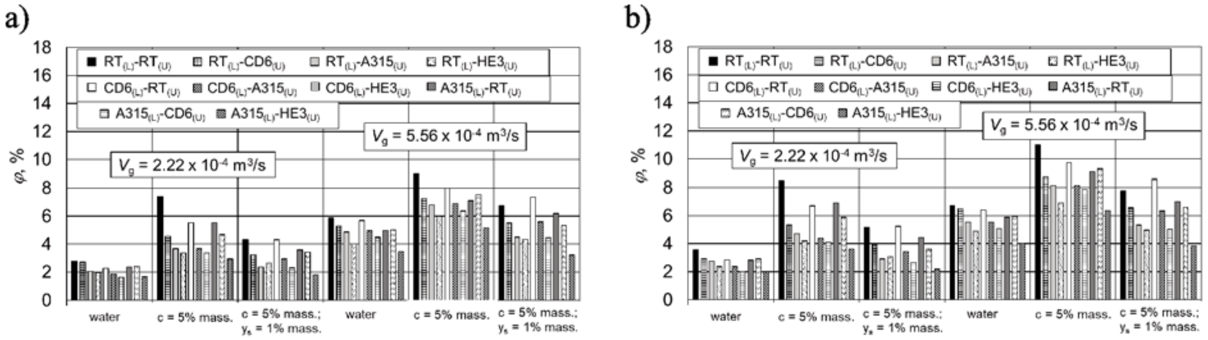

Figure 2. Dependence of φ = f(types of liquid or biophase-liquid); a) n = 10 1/s; b) n = 12 1/s

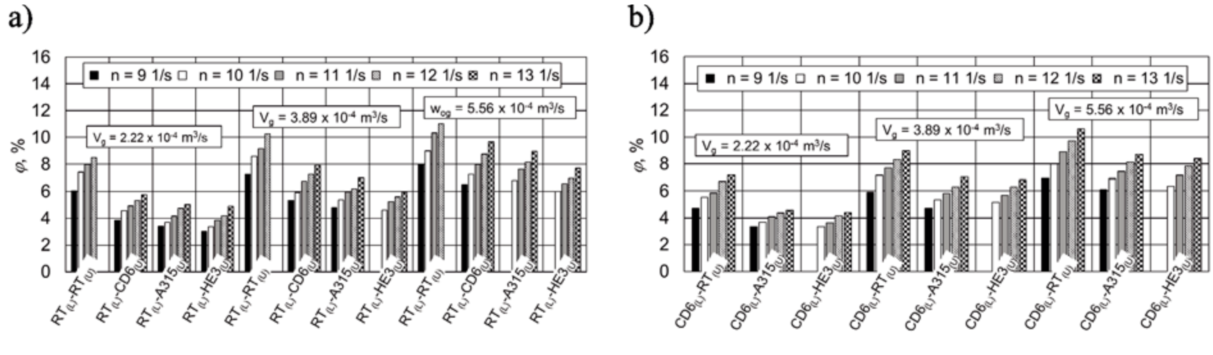

Figure 3. Dependence of φ = f(configurations of agitators); c = 5% mass

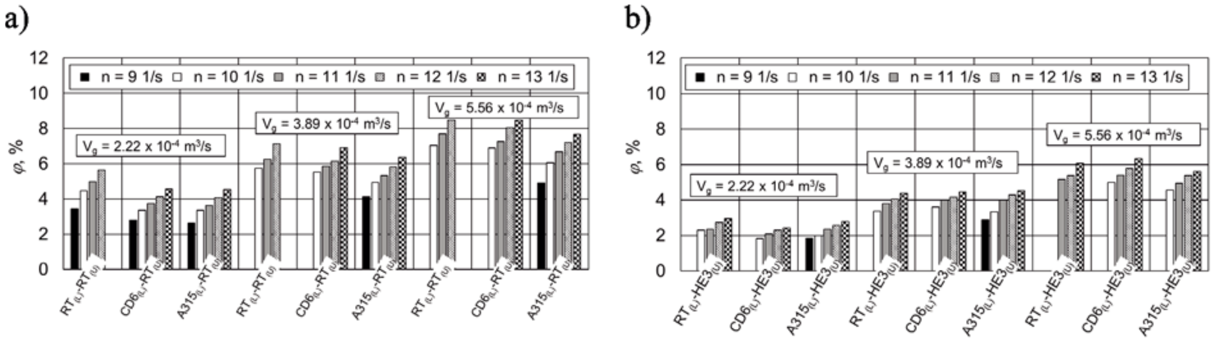

Figure 4. Dependence of φ = f(configurations of agitators); c = 2.5% mass

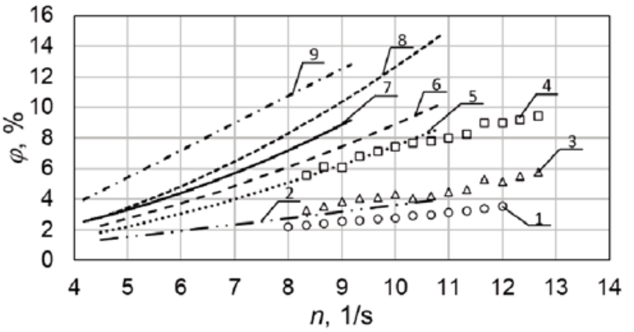

Figure 5. Dependence of φ = f(n); V_g = 2.22 x 10^{-4} m^3/s; RT$_{(L)}$-RT$_{(U)}$; D = 0.288 m; 1 – water; 2 – 2% mass. CMC[40]; 3 – 5% aqueous solution of sucrose -1% mass. yeast suspension; 4 – 5% mass. aqueous solution of sucrose; 5 – 0.2 kmol/m^3 Na_2SO_4[40]; 6 – 0.5 kmol/m^3 Na_2SO_4[40]; 7 – 40% mass. aqueous solution of glucose syrup[41, 42]; 8 – 50% aqueous solution of glycerine[40]; 8 – 60% mass. aqueous solution of glucose syrup[41, 42]

results, it was found that the highest values of the gas hold-up were obtained for the agitated vessel in which two Rushton turbine agitators (RT$_{(L)}$-RT$_{(U)}$) were mounted on the shaft. Comparing the results obtained for all agitators configurations (c = 5% by mass; Fig. 3), it can be concluded that in most cases, higher values of the gas hold-up were obtained when the Rushton turbine (RT) agitator was mounted on the shaft as the lower one (Fig. 3a). Replacing the Rushton top turbine agitator with Smith turbine agitators (CD6), A315 or HE3 resulted in lower values of the gas hold-up by approximately 38% (CD6), 47% (A315) and 52% (HE3) respectively – for V_g = 2.22 x 10^{-4} m^3/s and by approximately 20% (CD6), 26% (A315) and 36% (HE3) – for V_g = 5.56 x 10^{-4} m^3/s. A similar tendency occurs when a Smith turbine agitator (CD6) is installed on the shaft as the lower agitator (Fig. 3b). In this case, the highest values were also obtained for the CD6$_{(L)}$-RT$_{(U)}$ configuration (by about 10–20% lower compared to the RT$_{(L)}$-RT$_{(U)}$ configuration). In systems with the lower CD6 agitator, the influence of the upper agitator is slightly less. It can be concluded that the change in the circulation generated by the upper agitator (from radial to axial) negatively affects the value of the gas hold-up. In addition, comparing the two configurations of the RT$_{(L)}$-CD6$_{(U)}$ and CD6$_{(L)}$-RT$_{(U)}$ agitators, it was found that the higher values of the gas hold-up (by about 23%, respectively – V_g = 2.22 x 10^{-4} m^3/s, 15% – V_g = 3.89 x 10^{-4} m^3/s, 10% – V_g = 5.56 x 10^{-4} m^3/s) were obtained for the CD6$_{(L)}$-RT$_{(U)}$ configuration. Also in the case of the results obtained for two agitators configurations RT$_{(L)}$-A315$_{(U)}$ and A315$_{(L)}$-RT$_{(U)}$, higher values of the gas hold-up (by about 25%; 17%; 7%, respectively) were obtained for A315$_{(L)}$-RT$_{(U)}$ configuration[24].

In the case of agitators configurations with an upper RT agitator (Fig. 4a), replacing the lower RT agitator with an agitator generating radial-axial liquid circulation, i.e. CD6 or A315, reduces the value of the gas hold-up. The influence of the lower agitator on the gas hold-up is slightly smaller than the influence of the upper agitator and amounts to: 24% (CD6) and 26% (A315) for V_g = 2.22 x 10^{-4} m^3/s, respectively; 7% (CD6) and 15% (A315) for V_g = 3.89 x 10^{-4} m^3/s; 4% (CD6) and 14% (A315) for V_g = 5.56 x 10^{-4} m^3/s. Replacing the upper RT agitator with the HE3 agitator results in a significant (even 2-fold) reduction in the gas hold-up (Fig. 4b). In this case, changing the lower agitator slightly affects the value of the gas hold-up. For higher values of the volumetric gas flow rate slightly higher gas hold-up values were found for the CD6$_{(L)}$-HE3$_{(U)}$ agitators configuration than for the other two configurations RT$_{(L)}$-HE3$_{(U)}$ and A315$_{(L)}$-HE3$_{(U)}$.

Figure 5 shows the influence of various gas-liquid systems on the gas hold-up for the RT$_{(L)}$-RT$_{(U)}$. agitator configuration. The gas hold-up is greatly influenced by the viscosity and concentration of the liquid phase and the ability or not of the two-phase system to coalesce. The gas-hold increases with the increase in viscosity and concentration of the liquid phase (air-glycerin[40], air- glucose syrup[41, 42]). Systems with the ability to coalesce (including air-water or air-CMC solutions)[40] are characterized by a relatively small gas hold-up, assuming a constant value of agitator speed. This share increases as the system's ability to coalesce gas bubbles decreases. In the case of systems with a limited ability to coalesce, the ability of a gas to coalesce decreases with increasing concentration[40–42].

Assuming a constant value of the agitator speed and a constant value of the volumetric gas flow rate, the gas hold-up φ increased with the increase in the sucrose concentration in the system and decreases when the yeast suspension is added to the system (Fig. 6). The increase or decrease in the value of the gas hold-up depended on the agitators configuration used and the volumetric gas flow rate. The largest (2.5 times) increase in the gas hold-up with an increase in sucrose concentration in the system was obtained for the RT$_{(L)}$-RT$_{(U)}$ agitators configuration and the lowest volumetric gas flow rate V_g = 2.22 x 10^{-4} m^3/s. The influence of the RT$_{(L)}$-RT$_{(U)}$ agitators configuration on the gas hold-up decreased with the increase in the volumetric gas flow rate and amounted to 95% for V_g = 3.89 x 10^{-4} m^3/s and 60% for V_g = 5.56 x 10^{-4} m^3/s, respectively. A slightly smaller effect of sucrose concentration on the gas hold-up was found for the A315$_{(L)}$-RT$_{(U)}$ and CD6$_{(L)}$-RT$_{(U)}$ agitators configurations. However, in the case of the configurations with a lower RT agitator and an upper CD6, A315 or HE3 agitator, the influence of sucrose concentration on the gas hold-up was much smaller and amounted to 69% (V_g = 2.22 x 10^{-4} m^3/s); 51% (V_g = 3.89 x 10^{-4} m^3/s); 34% (V_g = 5.56 x 10^{-4} m^3/s) for the RT$_{(L)}$-CD6$_{(U)}$ agitators configuration and the other two configurations, respectively: 75%; 43% 35% for RT$_{(L)}$-A315$_{(U)}$ and 76%; 52% 47% for RT(L)-HE3$_{(U)}$. A comparable

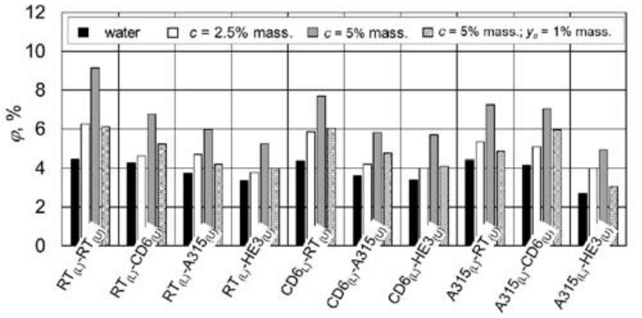

Figure 6. Dependence of φ = f(configurations of agitators); n = 11 1/s; V_g = 3.89 x 10^{-4} m^3/s

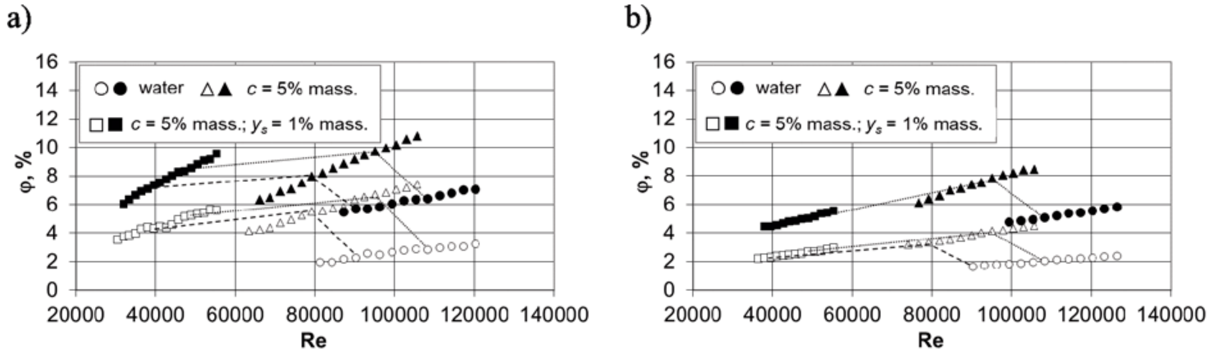

Figure 7. Dependence of φ = f(Re); empty – V_g = 2.22 x 10^{-4} m^3/s; full – V_g = 5.56 x 10^{-4} m^3/s a) $CD6_{(L)}$-$RT_{(U)}$; b) $Cd6_{(L)}$-$HE3_{(U)}$; dash line – n = 10 1/s; dot line – n = 12 1/s

effect of sucrose concentration on the gas hold-up was also obtained when the lower RT agitator was replaced with an A315 or CD6 agitator. In this case, the increase in sucrose concentration increased the gas hold-up by: 93%; 68% 51% for $A315_{(L)}$-$CD6_{(U)}$; 76%; 79% 52% for $A315_{(L)}$-$HE3_{(U)}$ or 92%; 60% 43% for $CD6_{(L)}$- $A315_{(U)}$. On the other hand, the addition of yeast to the system caused, in most cases, a decrease in the value of the gas hold-up by about 20–40%.

The influence of the Reynolds number on the gas hold-up is presented in Figure 7. Due to different values of density and dynamic viscosity coefficient, the range of the Reynolds number changed depending on the tested system. In the figure, dashed and dotted lines indicate the values of the gas hold-up for a constant value of the agitator speed. Only for Newtonian liquids, it was possible to determine how the value of the gas hold-up increases with an increase in the Reynolds number. Assuming a constant value of the Reynolds number, adding sucrose to water increases the gas hold-up by 1.5 to 3 times. A greater effect of sucrose on the gas hold-up was observed for lower values of the volumetric gas flow rate. Adding even a small amount of yeast (1% mass) to the 5% aqueous solution of sucrose-air system resulted in comparable values of the gas hold-up being obtained at 1.5–2 times lower values of the Reynolds number. Adding yeast to the system causes a more than two-fold increase in the value of the liquid's dynamic viscosity coefficient and a change in the liquid's properties from Newtonian to non-Newtonian.

The effect of gas flow number Kg, Weber number We, the concentration of aqueous sucrose solution c, and concentration of yeast suspension y_s on the gas hold-up, for a gas-liquid and gas-biophase-liquid systems, was developed as the relationship:

$$\varphi = x_1 \cdot \mathrm{Kg}^{x_2} \cdot \mathrm{We}^{x_3} \cdot (1 + c)^{x_4} \cdot (1 + x_5 \cdot y_s) \qquad (4)$$

The values of the coefficients (x_1, x_5) and exponents (x_2, x_3, x_4), and the average relative error of the equation are given in Table 3.

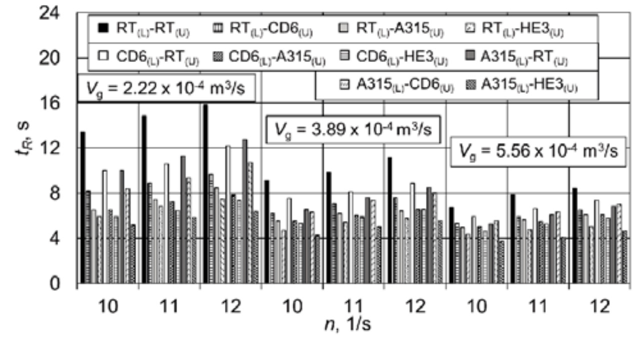

Figure 8. Dependence of t_R = f(n); c = 5% mass

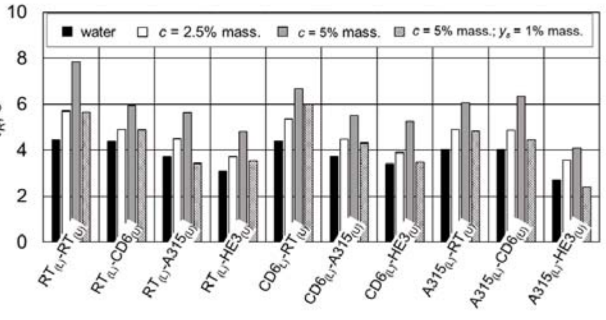

Figure 9. Dependence of t_R = f(configurations of impeller); n = 11 1/s; V_g = 5.56 x 10^{-4} m^3/s

In all analysed cases, the average residence time of the gas bubbles in the system increased with the increase in the agitator speed and the addition of sucrose to the system, while it decreased with the increase in the volumetric gas flow rate in the agitated vessel and the addition of yeast to the system (Figs. 8, 9). The longest average residence time of the gas bubbles in the agitated vessel was found for the $RT_{(L)}$-$RT_{(U)}$ agitators configuration. For this configuration, assuming n = const, increasing the volumetric gas flow rate in the vessel from V_g = 2.22 x 10^{-4} m^3/s to V_g = 5.56 x 10^{-4} m^3/s resulted in a decrease in the average residence time of the gas bubbles in the system by approx. 50% (Fig. 8). In the case of other agitators configurations, increasing the volumetric gas flow rate z shortened the average residence time of the gas bubbles in the system by about 20–30%. Based on the values of the average residence time of the gas bubbles in the system for the $RT_{(L)}$-$RT_{(U)}$ agitators configuration, with n = const, the values obtained for the configurations of the agitators, in which the CD6, A315 or HE 3 agitators were mounted on the shaft as the upper ones, it was found that the average residence time of the gas bubbles in the system decreased by 39%; 49%; 54% (for V_g = 2.22 x 10^{-4} m^3/s) for $RT_{(L)}$-$CD6_{(U)}$, 31% ; 40%; 47% (for V_g = 3.87 x 10^{-4} m^3/s) for $RT_{(L)}$-$A315_{(U)}$ and 23% ; 24%; 38% (for V_g = 5.56 x 10^{-4} m^3/s) for $RT_{(L)}$-$HE_{(U)}$. In contrast, in the configuration with the upper RT agitator, replacing the lower RT agitator with a CD6 or A315 agitator resulted in a decreased in bubble residence time in the system by approximately 25%; 23% (for V_g = 2.22 x 10^{-4} m^3/s), 19% ; 25% (for V_g = 3.87 x 10^{-4} m^3/s) and 15% ; 22% (for V_g = 5.56 x

Table 3. Values of coefficients x_1, x_5 and exponents x_2, x_3 and x_4 in Eq. 4, the average relative error and ranges of gas flow number Kg, Weber number We

No	Configurations of agitators	x_1	x_2	x_3	x_4	x_5	$\pm\Delta$
1.	$RT_{(L)}$-$RT_{(U)}$	5.81×10^{-4}	0.43	0.79	13.84	–24.60	8
2.	$RT_{(L)}$-$CD6_{(U)}$	6.66×10^{-4}	0.64	0.85	8.66	–8.05	9
3.	$RT_{(L)}$-$HE3_{(U)}$	9.45×10^{-4}	0.62	0.76	9.54	–16.80	6
4.	$CD6_{(L)}$-$RT_{(U)}$	8.22×10^{-4}	0.58	0.80	10.81	–5.18	7
5	$CD6_{(L)}$-$HE3_{(U)}$	5.97×10^{-4}	0.80	0.90	11.26	–21.73	8

Range: $c \in <0; 0.05>$; Kg $\in <0.019; 0.078>$; We $\in <600; 2200>$

10^{-4} m^3/s). Assuming V_g = const, increasing the agitator speed from 10 to 12 1/s resulted in a 20–30% increase in residence time (Fig. 8).

Among the four values changed during the tests, the greatest impact on the average residence time of gas bubbles in the system was observed when sucrose was added to the vessel (Fig. 9). The highest effect of sucrose concentration on the average residence time of gas bubbles was found for the $RT_{(L)}$-$RT_{(U)}$ agitators configuration and the lowest gas flow rate $V_g = 2.22 \times 10^{-4}$ m^3/s. The effect of sucrose concentration on the average residence time of gas bubbles decreased with an increase in the volumetric gas flow rate (e.g. $RT_{(L)}$-$A315_{(U)}$ was 78%; 61%; 50% respectively for $V_g = 2.22 \times 10^{-4}$ m^3/s; 3.89×10^{-4} m^3/s; 5.56×10^{-4} m^3/s). The addition of yeast suspension to the system reduced the average residence time of gas bubbles by approximately 20–40%.

CONCLUSIONS

The values of the gas hold-up and the average residence time of gas bubbles depend differently on the agitator speed, the gas flow rate, the concentration of sucrose in the aqueous solution and the concentration of yeast suspension. Gas hold-up increased with the increase agitator speed, volumetric gas flow rate and addition of sucrose to the system, while it decreased when yeast suspension is added to the aqueous sucrose-air system. The average residence time of gas bubbles increased with the increase of the agitator speed and sucrose concentration in the system, while it decreased with the increase of volumetric gas flow rate and the addition of yeast to the two-phase system. The highest values of the gas hold-up and the longest average residence time of gas bubbles were obtained for the $RT_{(L)}$-$RT_{(U)}$ agitators configuration. Replacing one of the RT agitators (upper or lower) with another agitator (CD6; A315; HE3) resulted in a significant (even two-fold) decrease in the gas hold-up and the average residence time of gas bubbles in the system. The values of the gas hold-up or average residence time of gas bubbles decreased in the direction of $RT_{(L)}$-$RT_{(U)}$ $RT_{(L)}$-$CD_{(U)}$ $RT_{(L)}$-$A315_{(U)}$ $RT_{(L)}$-$HE_{(U)}$ or $RT_{(L)}$-$RT_{(U)}$ $CD6_{(L)}$-$RT_{(U)}$ $A315_{(L)}$-$RT_{(U)}$ i.e. when the agitator producing radial liquid circulation was changed first to the agitator producing radial-axial liquid circulation, and finally the agitator producing to axial liquid circulation.

SYMBOLS

a – length of agitator blade, m
B – width of the baffle, m
b – width of agitator blade, m
c – sucrose concentration, % mass., $kmol/m^3$
D – inner diameter of the agitated vessel, m
d – diameter of the agitator, m
d_d – sparger diameter, m
e – off-bottom clearance of gas sparger, m
H – liquid height in the vessel, m
h_1 – distance of the lower agitator from the bottom, m
h_2 – distance of the upper agitator from the bottom, m
h – the height of a gas-liquid (gas-biophase-liquid) mixture in the agitated vessel, m
i – number of agitators
J – number of baffles
n – agitator speed, 1/s
t_R – average residence time of gas bubbles, s
V_L – volume of the liquid in the vessel, m^3
V_g – volumetric gas flow rate, m^3 /s
y_s – yeast concentration, % mass.
Z – number of agitator blades

Greek symbols

β – pitch of the agitator blade, deg
η – dynamic viscosity, Pas
φ – gas hold-up
ϱ – density, kg/m^3
σ – surface tension, N/m

Dimensionless numbers

$Kg = \frac{\dot{V}_g}{nd^3}$ – gas flow number

$We = \frac{n^2 d^3 \rho}{\sigma}$ – Weber number

$Re = \frac{nd^2 \rho}{\eta}$ – Reynolds number

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