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# An Effect of Different Factors on The Production of Mechanically Agitated Multiphase Biophase – Gas – Liquid Systems

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The effects of different factors on the production of mechanically agitated multiphase biophase-gas-liquid systems were experimentally studied. The following factors were taken into account: impeller speed *n*, gas flow rate $V_g$, type and number of the high speed impeller(s), height *H* of the fluid in the baffled vessel, sucrose concentration *x* and concentration *c* of the yeast suspension. Gas hold-up $\varphi$ and residence time $t_R$ were evaluated graphically and mathematically.

## 1. Introduction

Mechanical agitation of multiphase systems (gas-liquid, solid-liquid, liquid-liquid and three phase gas-solid-liquid systems) is commonly used in many chemical and biochemical processes. Processes occurring in such systems are studied using theoretical, numerical (Kasat et al. (2008); Gelves et al. (2014)) and experimental (Busciglio et al. (2017)) methods. Different factors, among others, a design of the agitated vessel, impeller type used and physical properties of the three phase system affect the production of such multiphase system. Especially, careful impeller choice and strict maintenance of the operating process conditions are required in a case of the biophase presence in the multiphase system (Gogate et al. (2000); Garcia-Ochoa and Gomez (2009)) because of, for example, the sensitivity of the biophase on the shear stresses (Campesi et al. (2009); Major-Godlewska et al. (2015)). For this reason, novel types of the impellers (Zhu et al. (2009); Gelves et al. (2014); Scargiali et al. (2014)) and impeller systems (Vrabel et al. (2000)) used in bioprocess applications are tested intensively. The effects of the multiphase system physical properties on the process characteristics were experimentally considered (Kiełbus-Rąpała et al. (2011)), but till now insufficient attention has been devoted to the systems with biophase. Cudak (2014) experimentally studied hydrodynamic characteristics for the multiphase system with biophase produced in the agitated vessel equipped with single impeller. Gaida et al. (2012) modelled hydrodynamic behaviour of a two-stage bioreactor with cell recycling.
Review of literature on mechanically agitated multiphase systems with biophase shows complexity of transport processes in such systems, therefore these systems require further studies. The aim of the study presented was to experimentally analyze the effects of different factors on the production of the mechanically agitated multiphase biophase – gas – liquid system. The following factors were taken into account: operating factors (agitator speed *n*, gas flow rate $V_g$), type and number of the high speed impeller(s), height *H* of the fluid in the baffled vessel, as well as physical properties of the fluid agitated (sucrose concentration *x* and concentration *c* of yeast suspension). Gas hold up $\varphi$ and residence time $t_R$ in a fluid agitated were experimentally determined.

## 2. Experimental

Measurements of the gas hold-up $\varphi$ and residence time $t_R$ of the gas bubbles were carried out in a baffled vessel of working volume $V_L$ = 0.02 m$^3$ or $V_L$ = 0.04 m$^3$. Transparent cylindrical agitated vessel of inner diameter *D* = 0.288 m was filled by liquid up to height *H* = *D* or *H* = 2*D* (Figure 1a). Four (*J* = 4) planar baffles of width *B* = 0.1*D* were symmetrically arranged immediately at inner cylindrical wall of the vessel. Multiphase

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system was agitated using high speed impeller(s) of diameter $d$ = 0.33$D$. Single impeller operating in the vessel with $H = D$ was placed at the height $h$ = 0.33$H$ from the flat bottom of the vessel. Two high speed impellers mounted on the common shaft of the vessel with $H$ = 2$D$ were arranged at the distances $h_1$ = 0.167$H$ and $h_2$ = 0.67$H$, respectively, from the flat bottom of the vessel. Four different types of the impellers were used: Rushton turbine (RT), Smith turbine (CD 6), A 315 and HE 3 impellers (Figures1b-d). Geometrical parameters of the impellers used are collected in Table 1. Upper impellers were radial flow Rushton turbine or axial flow HE 3 impeller. Rushton turbine, CD 6, A 315 or HE 3 impellers were used as lower impellers in case of the system with two impellers on the common shaft and as single impellers in the agitated vessel with $H$ = $D$. The following configurations of two impellers on the common shaft were tested: $RT_{(lower,\ (l))}$ – $RT_{(upper,\ (u))}$; $RT_{(l)}$-HE $3_{(u)}$; CD $6_{(l)}$-HE $3_{(u)}$; A $315_{(l)}$-HE $3_{(u)}$. Gas sparger shaped in the form of the ring of diameter $d_d$ = 0.7$d$ was located at half distance between lower impeller and bottom of the agitated vessel.
Liquid phases were distilled water and aqueous solution of sucrose with concentration 1.5 % (mass fraction). Air, as gas phase, and yeast suspension with concentration 0.75 % or 1.5 % (mass fraction) as biophase were used as dispersed phases. Measurements were carried out for four different values of gas flow rate ($V_g$ [m$^3$/s]$\in$ <1,39 x $10^{-4}$; 5,56 x $10^{-4}$>) and different values of the impeller speed $n$ within the turbulent fluid flow in the agitated vessel. For each type of impeller and system of two impellers, the lowest impeller speeds corresponded to conditions of the gas bubbles good dispersion in the vessel.

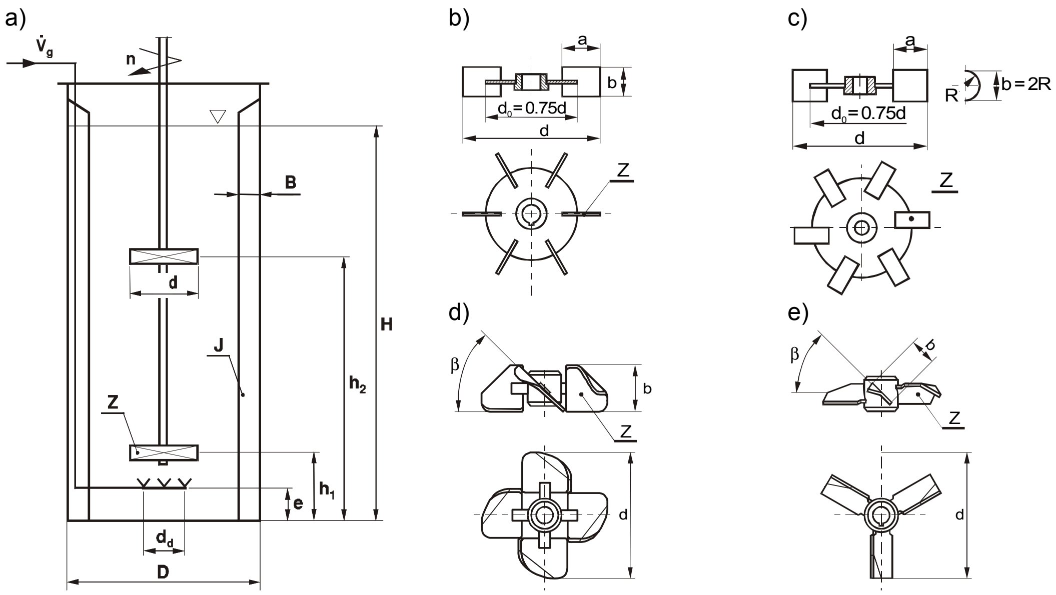


*Figure 1: Agitated vessel and impellers used in the study; a) geometrical parameters of the vessel; b) Rushton turbine; c) Smith turbine (CD 6 impeller); d) A 315 impeller; e) HE 3 impeller*

*Table 1: Geometrical parameters of the impellers use in the study*

| No. | Impeller | $d/D$ | $a/d$ | $b/d$ | $Z$ | $\beta$ | comments |
|---|---|---|---|---|---|---|---|
| 1. | Rushton turbine RT | 0.33 | 0.25 | 0.2 | 6 | | |
| 2. | Smith turbine CD 6 | 0.33 | 0.25 | 0.2 | 6 | | $R$=$b$/2 |
| 3. | A 315 | 0.33 | | 0.34 | 4 | 45 | |
| 4. | HE 3 | 0.33 | | 0.2 | 3 | 30 | |

The gas hold-up $\varphi$ was determined from the following definition

$$\varphi = \frac{V_{b-g}}{V_{b-g} + V_L} = \frac{h_{b-g}}{h_{b-g} + H} \tag{1}$$

where $V_{b\text{-}g}$ denotes the volume of both dispersed phases (gas phase and biophase), $V_L$ – volume of the liquid phase; $h_{b\text{-}g}$ – difference between heights of multiphase and liquid phase systems; $H$ – liquid height in the agitated vessel. The averaged value of the gas hold-up was determined from 10 readings of the multiphase

mixture height $h_{b-g}$ in the agitated vessel. Confidence intervals were estimated (according to definition $h_{b-g}= h_m \pm s(h_{b-g})t$, where $h_m$ – mean value of mixture height, $s(h_{b-g})$ – standard deviation, $t$ = 2.2622 – value of Student test) for each series of 10 readings. The lowest value of the confidence interval, ascribed to $h_{b-g}$= 10.2 ± 0.95, was obtained for the following data: impellers configuration A $315_{(l)}$-HE $3_{(u)}$, air-water, $V_g$ = 1.39 x $10^{-4}$ $m^3/s$, $n$ = 10.33 1/s. The highest value of the confidence interval, ascribed to $h_{b-g}$= 83.8 ± 5.99, corresponded to the follo wing data: impellers configuration $RT_{(l)}$-$RT_{(u)}$, 1.5% yeast suspension- air-1.5% aqueous solution of the sucrose, $V_g$ = 5.56 x $10^{-4}$ $m^3/s$, $n$ = 12.33 1/s.
Residence time $t_R$ [s] was calculated as follows (Alves et al. (2004))

$$t_R = \frac{V_L \varphi}{V_g (1-\varphi)} \tag{2}$$

where $V_g$ [$m^3/s$] denotes gas flow rate, $V_L$ [$m^3$] – volume of the liquid phase, $\varphi$ – gas hold-up.

## 3. Results and discussion

In total, about 1500 experimental points of the gas hold-up and residence time were obtained. On the basis of the experimental results, an analysis of the effects of the considered factors on the production of the mechanically agitated biophase – gas – liquid system was carried out.

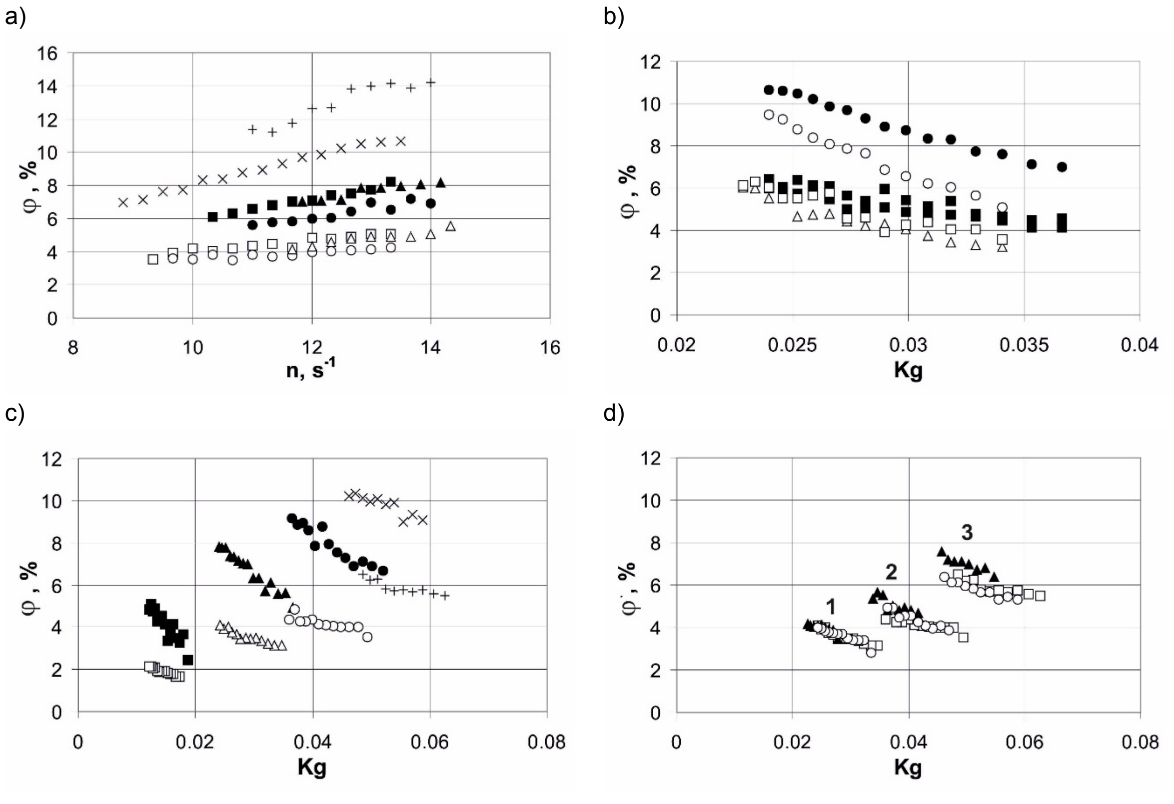


*Figure 2: Gas hold-up as a function of the impeller speed $\varphi$ = f(n) and gas hold-up as a function of the gas flow number $\varphi$ = f(Kg) for: a) 1.5% yeast suspension-air-1.5% aqueous solution of the sucrose; H/D = 2; o, □, Δ, x – $V_g$ = 2.78 x $10^{-4}$ $m^3/s$; •, ■, ▲, + – $V_g$ = 5.56 x $10^{-4}$ $m^3/s$; Δ, ▲ – $CD6_{(l)}$-$HE3_{(u)}$; □,■ – $RT_{(l)}$-$HE3_{(u)}$; •, o – A $315_{(l)}$-$HE3_{(u)}$; x,+ – $RT_{(l)}$-$RT_{(u)}$; b) $V_g$ = 2.78 x $10^{-4}$ $m^3/s$; o, □, Δ - H/D = 1; RT; •, ■, ▲- H/D = 2; $RT_{(l)}$-$RT_{(u)}$; □, ■ – air-1.5% aqueous solution of the sucrose; Δ, ▲ – 1.5% yeast suspension-air-0.75% aqueous solution of the sucrose; •, o – 1.5% yeast suspension-air-1.5% aqueous solution of the sucrose; c) 0.75% yeast suspension-air-1.5% aqueous solution of the sucrose ; o, □, Δ, + – $RT_{(l)}$-$HE3_{(u)}$; •, ■, ▲, x – $RT_{(l)}$-$RT_{(u)}$; □, ■ – $V_g$ = 1.39 x $10^{-4}$ $m^3/s$; Δ, ▲ – $V_g$ = 2.78 x $10^{-4}$ $m^3/s$; •, o – $V_g$ = 4.17 x $10^{-4}$ $m^3/s$; +, x – $V_g$ = 5.56 x $10^{-4}$ $m^3/s$; d) 0,75% yeast suspension-air-1.5% aqueous solution of the sucrose; o – $A315_{(l)}$-$HE3_{(u)}$; ▲ – $CD6_{(l)}$-$HE3_{(u)}$; □ – $RT_{(l)}$-$HE3_{(u)}$; 1 – $V_g$ = 2.78 x $10^{-4}$ $m^3/s$; 2 – $V_g$ = 4.17 x $10^{-4}$ $m^3/s$; 3 – $V_g$ = 5.56 x $10^{-4}$ $m^3/s$*

The dependence of the gas hold-up $\varphi$ in the three phase 1.5 % yeast suspension-air-1.5 % aqueous solution of sucrose system on the impeller speed $n$ is presented in Figure 2a for two different values of the gas flow rate $V_g$ and four different configurations of two impellers on the common shaft. The data $\varphi = f(n)$ show that gas hold-up $\varphi$ increases with the increase of both impeller speed $n$ and gas flow rate $V_g$ for all the systems of impellers tested. However, the highest values of the gas hold-up $\varphi$ correspond to the system of two Rushton turbines (RT) and the lowest – to the system with lower A 315 and upper HE 3 impellers. Two Rushton turbines on the common shaft generate strong radial circulation of the fluid in the agitated vessel, whereas the system of A $315_{(l)}$ – HE $3_{(u)}$ impellers is characterized by considerable component of the down-pumping axial flow of the fluid in the vessel. Comparing to the A $315_{(l)}$ – HE $3_{(u)}$ impellers system, slightly better results of the gas dispersion in the fluid can be obtained for both CD $6_{(l)}$ – HE $3_{(u)}$ and $RT_{(l)}$ – HE $3_{(u)}$ impellers system.

The dependences of the gas hold-up $\varphi$ as a function of the gas flow number $Kg$ (= $V_g/nd^3$) are compared in Figure 2b for different concentration $c$ of yeast suspension, as well as for both two Rushton turbines on the common shaft (filled points, $H/D$ = 2) and single Rushton turbine (empty points) operating in the vessel of $H/D$ = 1. These results represent data for the constant value of the gas flow rate $V_g$ equal to 2.78 x $10^{-4}$ $m^3/s$, therefore in this case the gas flow number $Kg$ decreases with the increase of the agitator speed $n$. Comparison of the results in Figure 2b shows that, assuming constant value of the $Kg$ number, higher values of the gas hold-up $\varphi$ correspond to the geometrical system with two Rushton turbines. For both geometrical systems ($H/D$ = 2 and $H/D$ = 1) and a given value of the $Kg$ number, the values of the gas hold-up $\varphi$ increase with the increase of the concentration $c$ of yeast suspension. Moreover, comparing both geometrical systems $H/D$ = 1 and $H/D$ = 2, the highest differences between the $\varphi$ values are observed for the highest value of the concentration $c$ equal to 1.5 %. This effect can be explained by the capability to gas bubbles coalesce decreasing in the three phase biophase-air-aqueous solution of the sucrose with the increase of the concentration $c$ of yeast suspension.

The effect of the upper impeller type on the gas hold-up is compared in Figure 2c where the dependence $\varphi = f(Kg)$ is presented for different gas flow rate $V_g$ and two different systems of the impellers on the common shaft, i.e. $RT_{(l)}$-$RT_{(u)}$ and $RT_{(l)}$-HE $3_{(u)}$, used to agitate 0.75 % yeast suspension-air-1.5 % aqueous solution of sucrose system. The gas hold-up $\varphi$ increases with the increase of the gas flow rate $V_g$ for both impeller systems, however, the values of the gas hold-up (assuming $V_g$ = const for both impeller systems) are significantly higher for the system with the upper radial flow Rushton turbine.

The effect of the lower impeller type cooperating with the upper down-pumping axial flow HE 3 impeller on the common shaft on the gas hold-up $\varphi$ is shown in Figure 2d for different values of gas flow rate $V_g$ and three configurations of two impellers: A $315_{(l)}$-HE $3_{(u)}$, CD $6_{(l)}$-HE $3_{(u)}$ and $RT_{(l)}$-HE $3_{(u)}$. The results, obtained for the 0.75 % yeast suspension-air-1.5 % aqueous solution of sucrose system, show that the system CD $6_{(l)}$-HE $3_{(u)}$ gives the best results of the gas hold-up for the highest gas flow rate $V_g$ = 5.56 x $10^{-4}$ $m^3/s$, whereas the values of $\varphi$ are clearly lower for both $RT_{(l)}$-HE $3_{(u)}$ and A $315_{(l)}$-HE $3_{(u)}$ systems. The differences of the $\varphi$ between all the three impeller systems radically diminish for the lowest gas flow rate $V_g$ = 2.78 x $10^{-4}$ $m^3/s$.

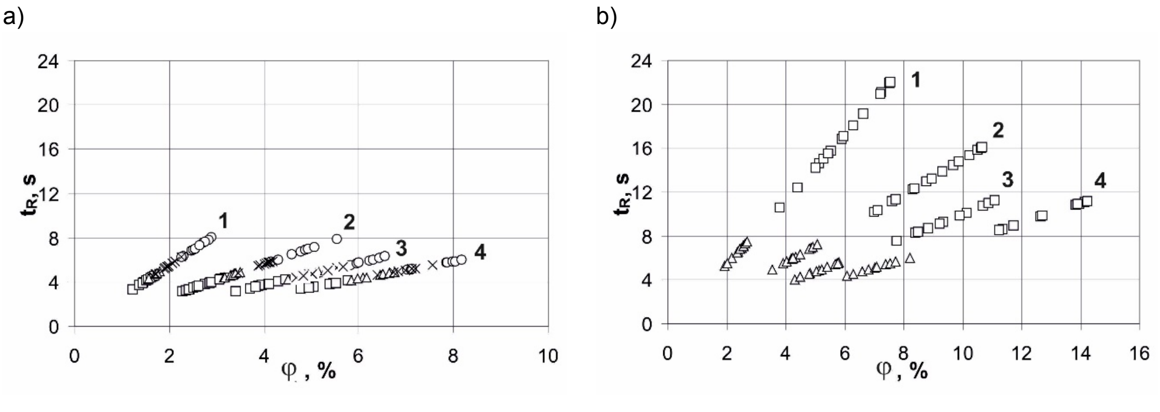


*Figure 3: The residence time as a function of the gas hold-up $t_R = f(\varphi)$; H/D=2; 1 – $V_g$ = 1.39 x $10^{-4}$ $m^3/s$; 2 – $V_g$ = 2.78 x $10^{-4}$ $m^3/s$; 3 – $V_g$ = 4.19 x $10^{-4}$ $m^3/s$; 4 – $V_g$ = 5.56 x $10^{-4}$ $m^3/s$; a) CD$6_{(l)}$-HE$3_{(u)}$; □ – air-distilled water; Δ – air-1.5% aqueous solution of the sucrose; x – 0.75% yeast suspension-air-1.5% aqueous solution of the sucrose; o – 1.5% yeast suspension-air-1.5% aqueous solution of the sucrose; b) 1.5% yeast suspension-air-1.5% aqueous solution of the sucrose; H/D = 2; Δ – $RT_{(l)}$-HE$3_{(u)}$; □ – $RT_{(l)}$-$RT_{(u)}$*

The dependence of the residence time $t_R$ as a function of the gas hold-up $\varphi = f(t_R)$ is presented in Figure 3 for the agitated vessel with two impellers on the common shaft and different values of the gas flow rate $V_g$. Figure 3a shows the data for the CD $6_{(l)}$-HE $3_{(u)}$ impellers system used to agitate two phase air-liquid systems (air-distilled water and 1.5 % aqueous solution of the sucrose), as well as three phase biophase-air-liquid systems (yeast suspension with concentration of 0.75 % or 1.5 %-air-1.5 % aqueous solution of sucrose). Figure 3b presents the results $\varphi = f(t_R)$ for three phase system (yeast suspension with concentration of 1.5 %-air- 1.5 % aqueous solution of sucrose) and two configurations of the impellers on the common shaft differing in the fluid circulation imposed by upper impeller. The data in Figure 3a show that, assuming constant value of the gas flow rate $V_g$ ($V_g$ = const), the lowest residence times $t_R$ correspond to air-distilled water system (sucrose concentration $x$ = 0 and yeast suspension concentration $c$ = 0) and to air-aqueous solution of the sucrose (sucrose concentration $x$ = 1.5 % and yeast suspension concentration $c$ = 0). For $V_g$ = const, values of the residence time $t_R$ increase with the increase of the concentration $c$ of the yeast suspension in three phase system. Moreover, the data in Figure 3a show that residence time $t_R$ increases with the decrease of the gas flow rate $V_g$, if the condition of the constant value of the gas hold-up $\varphi$ ($\varphi$ = const) is maintained in the compared systems. As the results presented in Figure 3b show the role of the fluid circulation generated by upper impeller is very significant. Namely, assuming $V_g$ = const, residence times $t_R$ higher from 1.25 to about 3 times are characteristic for upper radial flow Rushton turbine compared to upper axial flow HE 3 impeller.

Experimental results of the gas hold-up $\varphi$, (expressed in volume fraction) as a function of the impeller speed $n$ [1/s], superficial gas velocity $w_{og}$ [m/s] (= $4V_g/\pi D^2$), sucrose concentration $x$ and concentration $c$ of yeast suspension, were approximated for each tested system of two impellers on the common shaft, in the form of the following equation (Meister et al. (1979); Kralj and Sincic (1984); Cudak (2014))

$$\varphi = m_1 \cdot n^{m_2} \cdot w_{og}^{m_3} \cdot (1 + m_4 \cdot x) \cdot (1 + m_5 \cdot c) \quad (3)$$

Values of coefficients $m_1$, $m_4$, $m_5$ and exponents $m_2$, $m_3$ in Eq. (3), as well as approximation error $\pm\Delta$ (calculated as mean relative error) for each configuration of impellers are collected in Table 2. Eq. (3) is applicable within the following range of the variables: impeller speed $7.7 < n$ [1/s] $<14$; superficial gas velocity $2.13 \times 10^{-3} < w_{og}$ [m/s] $< 8.54 \times 10^{-3}$; sucrose concentration $0 < x < 0.015$; concentration of yeast suspension $0 < c < 0.015$. An analysis of the exponent $m_2$ at impeller speed $n$ shows that values of $m_2$ differ slightly only for tested configurations of the impellers. The effect of the sucrose concentration $x$ on the gas hold-up $\varphi$ is similar for the all impeller configurations and it corresponds to the increase of gas hold-up of about 24 %. Gas hold-up $\varphi$ increases with the increase of the yeast suspension concentration $c$, but this effect is differentiated depending on the configuration of the impellers. The highest increase of the $\varphi$ (on the level of 35 %) corresponds to the two Rushton turbines on the common shaft and the smallest one (about 12 %) is obtained for the system of A $315_{(l)}$ and HE $3_{(u)}$ impellers. These dependencies give the increase of gas hold-up about 25 % or 19 %, respectively, for the systems with upper HE 3 impeller and lower RT or CD 6.

*Table 2: Values of coefficients $m_1$, $m_4$, $m_5$ and exponents $m_2$, $m_3$ in Eq. (3)*

| Configuration of impellers | $m_1$ | $m_2$ | $m_3$ | $m_4$ | $m_5$ | $\pm\Delta$% |
|---|---|---|---|---|---|---|
| $RT_{(l)}$-$RT_{(u)}$ | 0.163 | 0.75 | 0.57 | 18.6 | 23.45 | 10 |
| $RT_{(l)}$-$HE3_{(u)}$ | 0.396 | 0.81 | 0.86 | 13.22 | 16.53 | 8 |
| $CD6_{(l)}$-$HE3_{(u)}$ | 0.723 | 0.77 | 0.96 | 15.24 | 12.78 | 8 |
| $A315_{(l)}$-$HE3_{(u)}$ | 0.181 | 0.73 | 0.68 | 16.32 | 7.99 | 7 |

## 4. Conclusions

The results of the experimental study of the effects of different factors on the production of mechanically agitated biophase-air-aqueous solution of sucrose system can be summarized within the range of the performed measurements as follows:

1. The system of two impellers on the common shaft should be recommended to production of the multiphase systems with biophase because significantly higher values of gas hold-up can be obtained compared to the vessel with single impeller.
2. High level of the gas hold-up and residence time is characteristic for the radial flow impellers operating at lower and upper positions on the shaft. Upper down pumping axial flow HE 3 impeller in combination with lower radial flow impeller (RT or CD 6) enables sufficient fluid circulation at upper part of the vessel and low power requirement, but clearly lower gas hold-up corresponds to those configurations compared to $RT_{(l)}$ – $RT_{(u)}$ system.

3. It results from Eq. (3) that gas hold-up increases about of 24 % with the sucrose concentration *x* increase compared to two phase system of air-distilled water for each tested impeller configurations.
4. Concentration *c* of yeast suspension significantly affects the increase of the gas hold-up in multiphase systems with biophase. Eq. (3) shows that the highest effect of the concentration *c* is obtained for both Rushton turbines ($RT_{(l)}$ – $RT_{(u)}$) configuration, the increase of $\varphi$ about 35 %) and the lowest one for the A $315_{(l)}$ – HE $3_{(u)}$ impellers (the increase of $\varphi$ about 12 %).

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