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HYDRODYNAMIC CHARACTERISTICS OF MECHANICALLY AGITATED AIR - AQUEOUS SUCROSE SOLUTIONS

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The aim of the research presented in this paper was determination of power consumption and gas hold-up in mechanically agitated aerated aqueous low concentration sucrose solutions. Experimental studies were conducted in a vessel of diameter 0.634 m equipped with high-speed impellers (Rushton turbine, Smith turbine or A 315). The following operating parameters were changed: volumetric gas flow rate (expressed by superficial gas velocity), impeller speed, sucrose concentration and type of impeller. Based on the experiments results, impellers with a modified shape of blades, e.g. CD 6 or A 315, could be recommended for such gas-liquid systems. Power consumption was measured using strain gauge method. The results of gas holdup measurements have been approximated by an empirical relationship containing dimensionless numbers (Eq. (2)).

Keywords: agitated vessel, aqueous solutions of sucrose, gas hold-up, power consumption

1. INTRODUCTION

Mixing in gas-liquid systems is applied in technologies associated with the chemical, food, pharmaceutical and petrochemical industries, as well as in biotechnology. It is used to intensify fermentation, sewage treatment, oxidation, nitration and other processes (Ahmed et al., 2010; Kamieński, 2004; Stręk, 1981).

Selection of the proper process parameters (for example power consumption or gas hold-up) which characterise the mixing operation in the agitated vessel allows to ensure appropriate conditions for conducting chemical and biochemical processes (Garcia-Ochoa and Gomez, 2009; Martin et al. 2008a,b; Montante et al., 2007, 2008; Raposo and Lima-Costa, 2012; Scargiali et al., 2007; Van't Riet, 1975).

To select a system characterised by lowest energy consumption, it is necessary to conduct measurements of power consumption. Such measurements can be performed using various methods, for example electric or strain gauge methods. The latter method consists of measuring the torque on the shaft of the impeller (Stręk, 1981). The power consumption depends on many factors, among others on the operating parameters of a process and physical parameters of a fluid, as well as the amount of gas supplied to the system. The impact of various parameters on power consumption has been the subject of much research (Adamiak, 2005; Adamiak and Karcz, 2007; Ascanio et al., 2004; Bouaifi and Roustan, 2001; Gill et al., 2008; Kamieński, 2004; Karcz and Siciarz, 2001; Markopoulos and Panntuflas, 2001; Nienow and Lilly, 1996; Roman and Tudose, 1997; Stręk, 1981; Vilaca et al., 2000; Yianatos, 2010). Typically adding gas phase to a liquid causes a decrease in power consumption as compared with results achieved for liquid phase alone. In the case of impeller sets mounted on a

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common shaft, the decrease in power consumption in gas-liquid systems depends on the impeller type and on the distance between impellers, as well as on the scale of an agitated vessel.

The gas hold-up depends on the type and geometric parameters of the impeller and the vessel, physical parameters of the fluid, impeller speed and on the amount of gas supplied to the system (Adamiak, 2005; Alves et al., 2002; Bouaifi et al, 2001; Fasano et. al., 2011; Garcia-Ochoa and Gomez, 2004; Hu et al., 2005; Kamieński and Niżnik, 2001; Karcz et al. 2004; Karcz J., 1998; Kerdouss et al., 2006; Newell and Grano, 2007a,b; Vasconcelos et al., 2000).

In gas-liquid systems produced in a vessel with one or more impellers, the main condition of their correct functioning is achieving uniform gas dispersion throughout the whole volume of the liquid. Dispersion of gas in liquid depends also on the type, size and location of gas sparger (Bao et al., 2012; Fasano et al., 2011; Kamieński and Niżnik, 2002; Kamieński, 2004; Major-Godlewska and Karcz, 2011; Moucha et al., 2003; Paglianti, 2002; Shewale and Pandit, 2006; Vinnett et al., 2012; Warmoeskerken, 1986; Yianatos et al., 2010). For gas-liquid systems, single impellers or impeller sets generating radial-axial circulation of the fluid in a vessel are often used. Such systems may include a standard Rushton turbine impeller or impellers with a modified shape of blades, e.g. CD 6 or A 315. Such impellers are preferred in processes involving microorganisms. They are characterised by lower shear stress as compared to those in turbine impellers.

Aqueous solutions of carbohydrates (glucose, fructose or sucrose) have practical application in molecular biology and biochemistry, food chemistry and technology, sugar refining and pharmaceutics (Laos et al., 2007). Molasses, in which the main component is sucrose, is one of the more valuable raw materials used in food, chemical and biotechnological industries, for example, to produce citric acid, baker's yeast or ethanol (Szewczyk, 2003). The first stage of aerobic yeasts cultivation takes place in batch bioreactors. This process is conducted at high sugar concentrations. However, the so-called Crabtree effect is likely to occur, resulting in sugar being metabolised into ethanol. Additionally, multiplication of yeasts at high sugar concentrations is relatively expensive. Therefore, yeasts cultivation usually takes place at low carbohydrate concentrations (Szewczyk, 2003). In yeast cultivation, it is also important to provide relevant aeration of the system.

Results of power consumption and gas hold-up measurements in stirred reactors published in the literature concern mainly model physical systems such as air-water or air-solutions of electrolytes. Since mechanically agitated air-aqueous sucrose solutions have not so far been sufficiently studied, it is fully justified to undertake experimental research on them.

The aim of the research presented in this paper is to determine power consumption and gas hold-up for mechanically agitated aerated aqueous sucrose solutions of low concentrations. The analysis concerns the impact of various parameters on process characteristics in an agitated vessel equipped with a high-speed impeller.

2. EXPERIMENTAL

The measurements of the process characteristics were carried out in an agitated vessel with the inner diameter $T = 0.634$ m and the working volume $V_L = 0.2$ m^3. The vessel, equipped with a flat bottom and four baffles of width $B = 0.1T$, was filled with a liquid up to the height $H = T$. Geometrical parameters of the agitated vessel are shown in Fig. 1.

Three high-speed impellers of the inner diameter $D = 0.33T$ (Fig. 2) were used in the study: Rushton turbine ($a/D = 0.25$, $b/D = 0.2$, $Z = 6$), Smith turbine ($a/D = 0.25$, $b/D = 0.2$, $R = b/2$, $Z = 6$) or A 315 ($b/D = 0.34$, $Z = 4$, $\beta = 45^o$). A radial flow in the vessel was generated by the Rushton or Smith turbines. A 315 impeller afforded a mixed flow. Each impeller was located at a distance $h = 0.33H$ from the bottom of the vessel. Gas was introduced into the liquid through a ring-shaped sparger of diameter $d_d = 0.7D$. The sparger with 44 holes of 2 mm in diameter was located at a distance of $e = h/2$ from the bottom of the vessel.

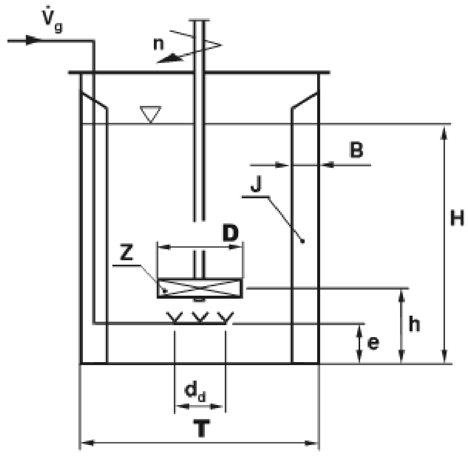

Fig. 1. Geometrical parameters of the agitated vessel

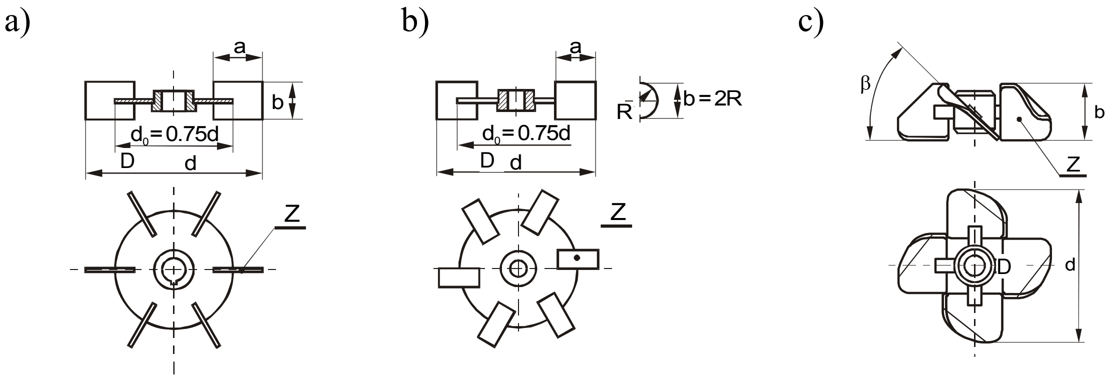

Fig. 2. Geometrical parameters of the impellers: a) Rushton turbine (RT), b) Smith turbine (CD 6), c) A 315

Aqueous solutions of sucrose with mass concentration of 7.5 and 10% were used in the experiments. Air was applied as a gas phase. The results obtained in this paper were compared with literature data (Cudak, 2011) received for such solutions with mass concentrations of 0, 1, 1.5, 2, 2.5, 5%. A two-phase system comprising of water and air is characterised by a capability of gas bubble coalescence. Systems containing aqueous solutions of sucrose behave as a non-coalescing system. In the whole range of the concentration, e.g. from 0 to 10%, physical parameters of the liquid phase changed in the following ranges: dynamic viscosity η_L [Pa·s] $\in <10^{-3}; 1.4\times10^{-3}>$, density ρ_L [kg/m^3] $\in <1000; 1040>$, surface tension σ_L [N/m] $\in <0.072; 0.076>$. The measurements were conducted for five values of the volumetric air flow rate $\dot{V}_g$ fed into the agitated vessel ($\dot{V}_g$ [m^3/s]$\in <5.56\times10^{-4}; 3.33\times10^{-3}>$, corresponding to superficial gas velocity w_{0g} [m/s]$\in <1.76\times10^{-3}; 10.55\times10^{-3}>$). The measurements were carried out within the turbulent regime of liquid flow in the agitated vessel ($Re \in <95000; 252000>$).

Power consumption was measured using the strain gauge method (Adamiak and Karcz, 2007). Gas hold-up was calculated from the following relationship

$$\varphi = \frac{H_g - H}{H_g} \tag{1}$$

The averaged value of gas hold-up was determined from 10 readings of the gas-liquid mixture height in the agitated vessel.

3. RESULTS AND DISCUSSION

The effects of the studied process parameters such as volumetric gas flow rate (expressed by superficial gas velocity), impeller speed, sucrose concentration, and type of impeller on power consumption and gas hold-up have been analysed based on approximately 1300 data points obtained in the study.

A dependence of the specific power consumption, P_g/V_L, as a function of the impeller speed at different values of w_{0g} is illustrated in Fig. 3. With an increasing impeller speed, the values of specific power consumption increase. The highest, approximately ten-fold growth in the value of P_g/V_L has been observed for the lowest superficial gas velocity ($w_{0g} = 1.76\times10^{-3}$ m/s), and the system with a Rushton turbine impeller (Fig. 3a). The effect of impeller speed on specific power consumption decreases with an increase of superficial gas velocity (cf. Fig. 3a and 3b). The effect of impeller type on P_g/V_L depends on the volumetric gas flow rate in the agitated vessel. For lower values of superficial gas velocity, the agitated vessel with the Rushton turbine is the most energy-consuming system (Fig. 3a). Along with the increasing gas flow rate the differences between the results determined for the agitated vessel with the Rushton (RT) and Smith (CD 6) turbine impellers (Fig. 3b) diminish. After exceeding the superficial gas velocity $w_{0g} > 5\times10^{-3}$ m/s, it can be noted that the specific power consumption, P_g/V_L, measured for the agitated vessel with a Smith turbine impeller is slightly higher than that found for the agitated vessel equipped with the Rushton turbine impeller (Fig. 3b). Assuming a constant value of impeller speed, a significant effect of gas flow rate supplied to the system on the specific power consumption (P_g/V_L) has been ascertained only in the case of the Rushton turbine impeller. For this impeller, an increase in the gas flow rate resulted in reduction of the value of P_g/V_L by half (cf. Fig. 3a and 3b).

The effect of impeller speed on specific power consumption, for all aqueous sucrose solution – air systems, was approximated as follows $P_g/V_L = C{\cdot}n^a$, where the exponents are equal to a = 3.01 (for the system with Rushton turbine or A 315 impeller) and a = 3.13(for the Smith turbine).

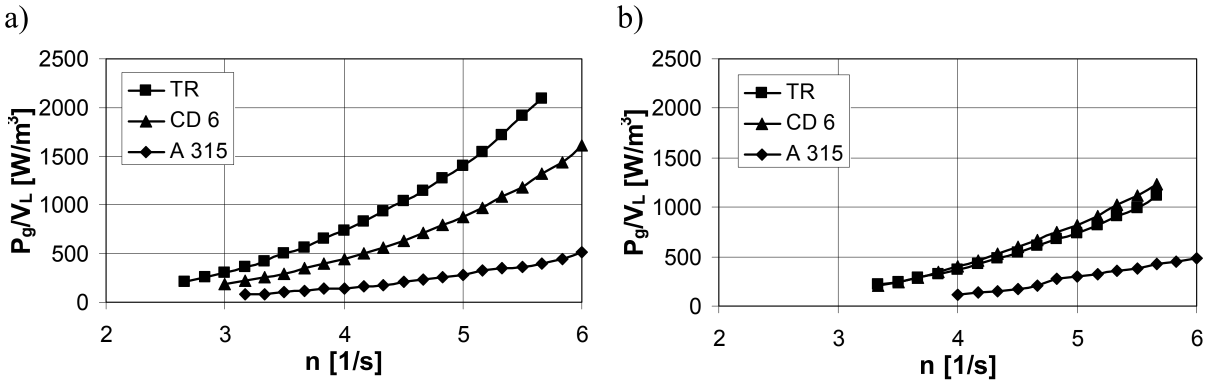

Fig. 3. Dependence $P_g/V_L = f(n)$ for the 10% aqueous solution of sucrose – air;
a) $w_{0g} = 1.76\times10^{-3}$ m/s; b) $w_{0g} = 5.27\times10^{-3}$ m/s

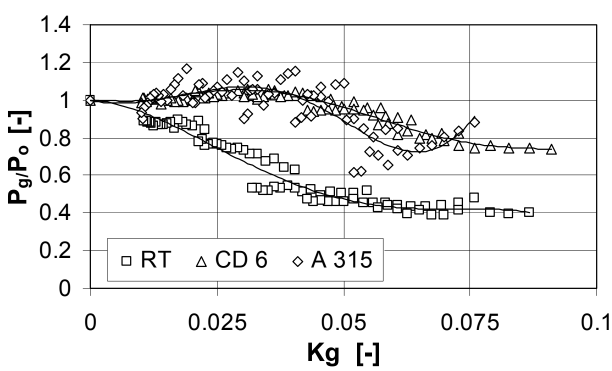

Fig. 4. Power characteristics for the 10% aqueous solution of sucrose - air system

Fig. 4 presents the characteristics of relative power consumption $P_g/P_0 = f(Kg)$ for 10% aqueous sucrose solution – air system. A decrease of power consumption caused by gas supply to an agitated liquid depends on the type of the applied impeller.

In an agitated vessel equipped with the Rushton turbine impeller, introduction of air into the system resulted in a substantial (approximately 60%) reduction in power consumption as compared to that when no air was fed into the system (P_0). Power consumption for this impeller decreased in the whole range of the values of gas flow number. The results of relative power consumption obtained for the agitated vessel equipped with the Rushton turbine show a typical decrease of power consumption with the increase of gas flow number Kg (Adamiak, 2005; Adamiak and Karcz, 2007; Vasconcelos et al., 2000). Compared to water-air systems, the decrease in relative power consumption for aqueous sucrose solutions-air system is about 50% larger (Adamiak and Karcz, 2007; Vasconcelos et al., 2000).

For the two other impellers, the relative power consumption, P_g/P_0, has the values below 1.0 only after exceeding values of $Kg \approx 0.05$. In the range of $Kg \in (0; 0.05)$ the results of power consumption measured for the gas-liquid system are comparable to and even by ca.15% higher than those obtained for the single-phase system. A decrease in power consumption for systems with a Smith turbine (CD6) or A 315 impeller is approximately three times lower than that observed for the Rushton turbine. It has also been found that the values of P_g/P_0 obtained for the agitated vessel equipped with A 315 impeller and at the highest values of w_{0g} increased with the increasing values of gas flow number Kg. Relatively strong instability in the system, characterised by the presence of areas with an non-uniform dispersion of gas bubbles, was observed in this case. In some places there were areas with high volumetric concentration of gas bubbles, while the so-called dead areas appeared in other places of the liquid phase.

Experimental results of relative power consumption were approximated as follows

$$\frac{P_g}{P_o} = a + \frac{b}{1 + c(1+x)Kg^d} + e(1+x)\sqrt{\frac{Kg}{Fr}} \tag{2}$$

The values of the coefficients *a, b, c, e* and exponent *d* in Eq. (2) are collected in Table 1. This equation describes the results of measurements within the following range: $Kg \in$ <0.01; 0.1>, $Fr \in$ <0.1; 0.8> and $x \in$ <0.01; 0.1>.

Table 1. Values of coefficients *a*, *b, c, e* and exponent *d* in Eq. (2)

No.	Impeller	*a*	*b*	*c*	*d*	*e*	$\pm\Delta\,\%$
2-1.	Rushton turbine	0.25	0.75	2594.7	2.26	0.16	5
2-2.	Smith turbine	0.25	0.75	3056.1	3.06	0.40	5
2-3.	A 315	0.25	0.75	8885.0	3.16	0.60	8

A dependence of $\varphi = f(P_g/V_L)$ for water – air systems as well as aqueous sucrose solution – air systems is illustrated in Fig. 5. A comparison of the results obtained for all impellers reveals that the values of gas hold-up increase even 2 or 3 times with the increase in specific power consumption P_g/V_L.

Assuming a constant value of P_g/V_L, the values of φ increase both along with the growing superficial gas velocity and the sucrose concentration in the solution. The impact of P_g/V_L on gas hold-up increases along with the increasing concentration of sucrose in the system (Fig. 5b, c, d). The effect of impeller type on gas hold-up, for aqueous solutions of sucrose, depends on the value of w_{0g}. A strong effect of the impeller type on gas hold-up can be observed for lower values of w_{0g}. On the other hand, with the increasing values of superficial gas velocity, the obtained values for the vessel equipped with RT or CD6 impellers are comparable. Regardless of the examined physical system, assuming a constant value of P_g/V_L, the highest values of gas hold-up have been obtained for A 315 impeller.

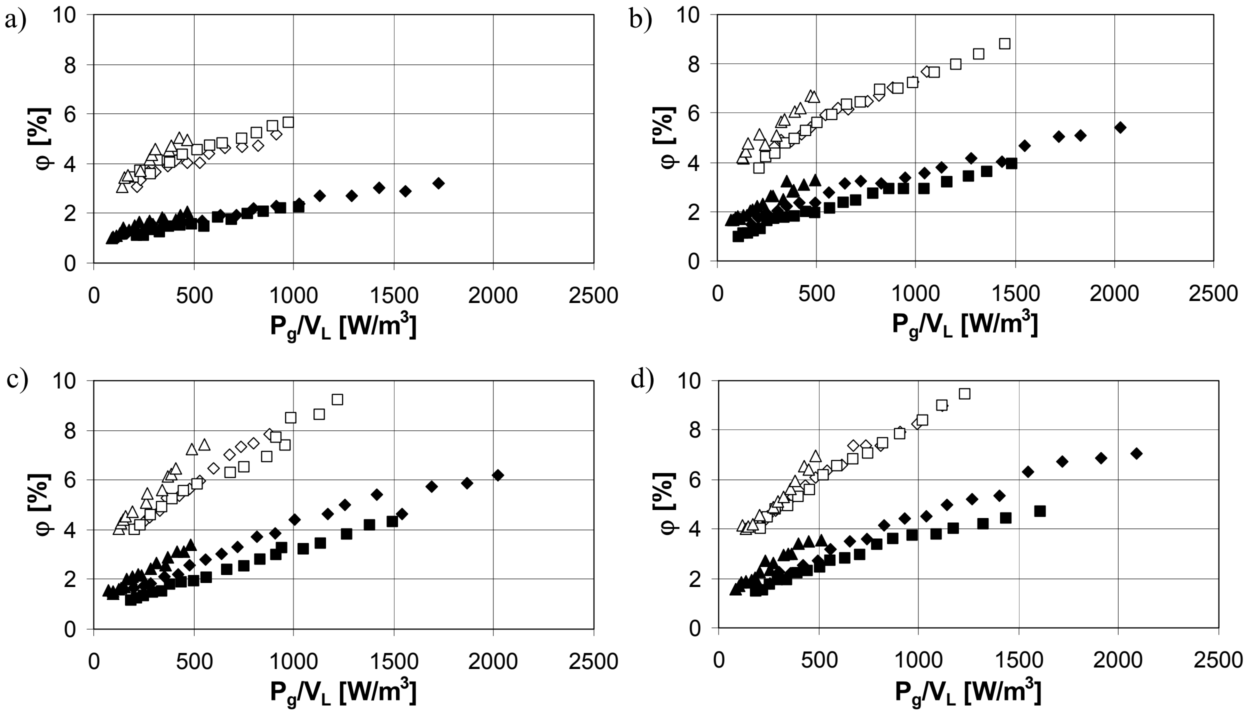

Fig. 5. Dependence $\varphi = f(P_g/V_L)$; a) distilled water – air; b) 5% aqueous solution of sucrose - air; c) 7.5% aqueous solution of sucrose - air; d) 10% aqueous solution of sucrose - air; ♦, ▲, ■ – $w_{0g} = 3.52\times10^{-3}$ m/s; ◊, Δ, □ – $w_{0g} = 7.03\times10^{-3}$ m/s; ♦, ◊– RT; ▲, Δ– A315; ■, □ – CD6

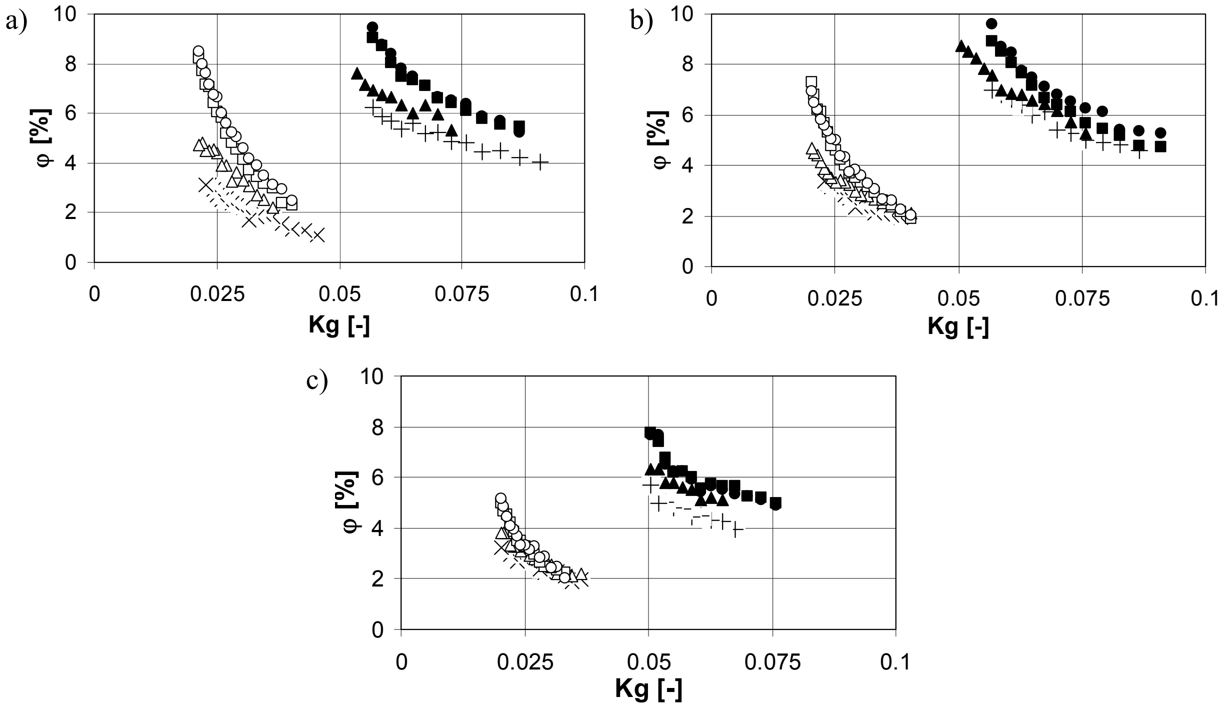

Fig. 6. Dependence $\varphi = f(Kg)$ for the systems: a) RT, b) CD 6, c) A 315; ×, + – distilled water – air; Δ, ▲ – 2.5% aqueous solution of sucrose - air; □, ■ – 7.5% aqueous solution of sucrose - air; ○, ● – 10% aqueous solution of sucrose - air; ×, □, Δ, ○; $w_{0g} = 3.52\times10^{-3}$ m/s; +, ■, ▲, ● – $w_{0g} = 8.79\times10^{-3}$ m/s

The effects of superficial gas velocity, sucrose concentration in the aqueous solution and the type of impeller on gas hold-up are depicted in Figs. 6 and 7. Measurements showed that assuming a constant value of *Kg*, gas hold-up increases with increased concentration of sucrose (Fig. 6).

Gas hold-up also increases along with the increasing w_{0g}. At higher concentrations of sucrose in the aqueous solution, for lower values of w_{0g}, a significantly larger impact of the impeller speed on gas hold-up has been observed. This effect decreases along with the increasing w_{0g}. Gas hold-up depends on the capability of gas bubbles to coalesce. For a given value of superficial gas velocity, higher values of gas hold-up are obtained for a non-coalescing system, e.g. aqueous solutions of sucrose.

The effect of the impeller type on gas hold-up depends on gas flow rate (superficial gas velocity) in the agitated vessel (Fig. 7). Assuming a constant value of *Kg*, the values of gas hold-up φ increase with the increase of superficial gas velocity w_{0g}. For lower values of superficial gas velocity, regardless of the examined gas-liquid system, the highest values of φ were observed for Rushton turbine impeller. Along with the increase of w_{0g} it can be noted that the values of gas hold-up for CD 6 impeller and Rushton turbine are comparable. The obtained values of φ for A 315 impeller, in the range of higher values of superficial gas velocity w_{0g}, are much lower than those received for the two remaining impellers.

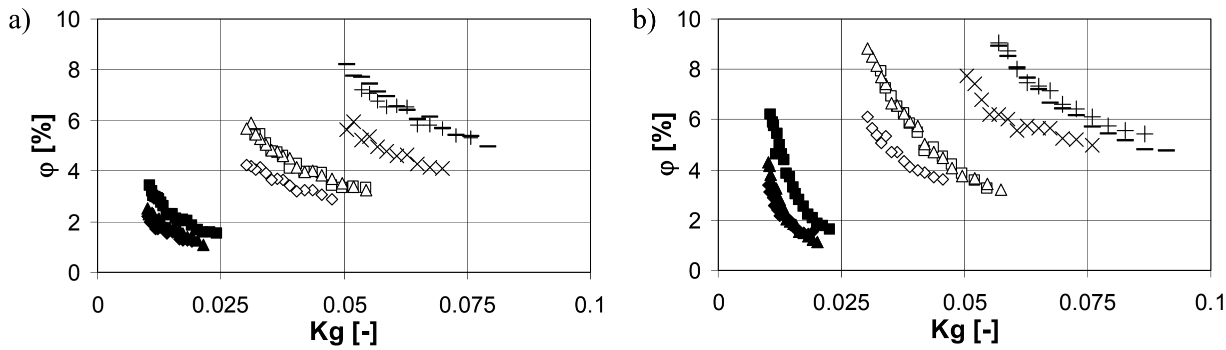

Fig. 7. The dependence $\varphi = f(Kg)$ for the systems: a) 1.5% aqueous solution of sucrose - air, b) 7.5% aqueous solution of sucrose - air; ■,▲,♦ – $w_{0g} = 1.76\times10^{-3}$ m/s; □,Δ,◊ – $w_{0g} = 5.27\times10^{-3}$ m/s; ×, +, - – $w_{0g} = 8.79\times10^{-3}$ m/s; +,□,■ – TR; -,Δ ,▲ – CD6; ×,◊ ,♦, – A 315

Measurement results of gas hold-up were approximated using dimensionless numbers as follows

$$\varphi = a \cdot Kg^{b} \cdot We^{c} \cdot (1 + d \cdot x)^{e} \cdot M^{g} \quad (3)$$

The values of the coefficients *a, d* and exponents *b*, *c*, *e, g* in Eq. (3) are collected in Table 2. Equation (3) describes measurements within the following range: $Kg \in$ <0.01; 0.1>, $We \in$ <780; 4530> and $M \in <3.65\times10^{-10};\ 6.32\times10^{-11}>$.

Table 2. Values of coefficient *a*, *d* and exponents *b*, *c*, *e*, *g* in Eq. (3)

No.	*x*	Impeller	*a*	*b*	*c*	*d*	*e*	*g*	$\pm\Delta\%$
3-1.	0.01 - 0.1	Rushton turbine	8.707×10^{-5}	0.40	0.88	15.75	0.54	-0.02	9
3-2.		Smith turbine	1.130×10^{-4}	0.67	0.99	9.54	0.61	-0.01	8
3-3.		A 315	5.154×10^{-4}	0.53	0.83	34.66	0.22	0.03	7

A comparison of exponents in Eqs. (3-1)–(3-3) (Table 2) shows that the Weber number *We* and the gas flow number *Kg* exert the greatest effect on gas hold-up. The values of the exponent *b* obtained for agitated vessel with the Rushton turbine are comparable with the data for the stable "3-3" structure recommended by Warmoeskerken (1986).

Gas hold-up significantly depends also on sucrose concentration, but is weakly influenced by the Morton number. Due to the fact that the impact of the Morton number on the hold-up is smaller than the relative error of the equation, this effect can be neglected.

The values of the gas hold-up, calculated from Eq. (3) and those obtained from experiments are compared in Fig. 8.

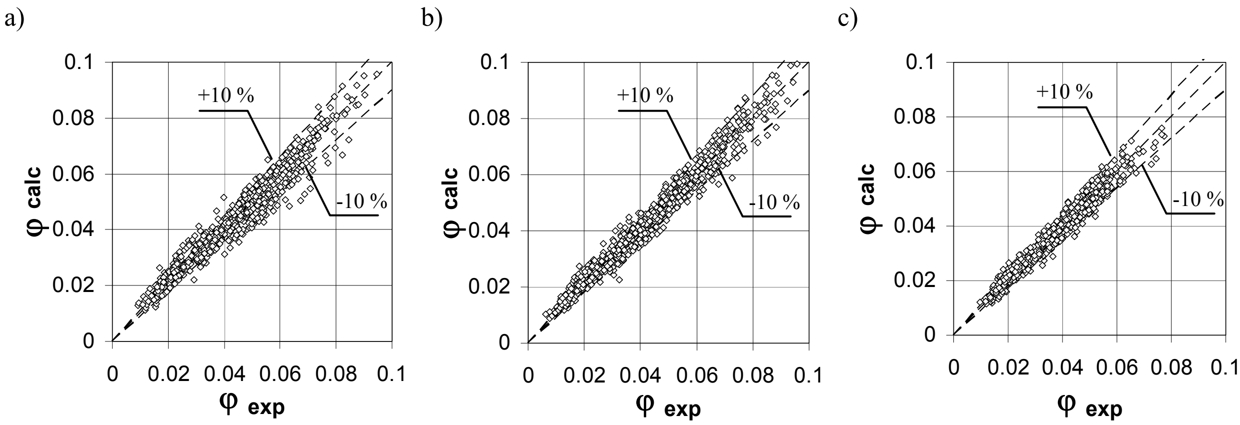

Fig. 8. Comparison of the experimental and calculated values of gas hold-up from Eq. (3);
a) RT; b) CD 6; c) A315

4. CONCLUSIONS

Proper operating and physical parameters of a process (for example when applied in yeasts production) in an agitated vessel can be selected on the basis of experimental results. Taking into account sensitivity of biological systems on shear stress, an impeller with a modified shape of blades, e.g. CD 6 or A 315, should be recommended instead of the Rushton turbine. In such systems an addition of gas phase to a liquid results in a insignificant fall of power consumption. Therefore it is more advantageous using an impeller with a modified shape of blades, e.g. CD 6 or A 315. Moreover, assuming a constant value of P_g/V_L, the highest values of gas hold-up could be achieved for the agitated vessel with an A 315 impeller. Regardless of the examined physical system, assuming a constant value of P_g/V_L, gas hold-up increases significantly (approximately by a factor of 2) with the increase of superficial gas velocity, while the concentration of sucrose in a solution has a minor effect on gas hold-up.

SYMBOLS

a	length of impeller blade, m
B	baffle width, m
b	width of impeller blade, m
D	impeller diameter, m
d_d	diameter of gas sparger, m
e	off-bottom clearance of gas sparger, m
H	liquid height in the agitated vessel, m
H_g	the height of a gas-liquid mixture in the agitated vessel, m
h	off-bottom clearance of the impeller, m
n	impeller speed, 1/s

P_0	power consumption for liquid phase, W
P_g	power consumption for the gas-liquid system, W
T	inner diameter of the agitated vessel, m
V_L	volume of the liquid in the vessel, m^3
$\dot{V}_g$	gas flow rate, m^3/s
w_{0g}	superficial gas velocity, $= 4\dot{V}_g / \pi T^2$, m/s
x	mass fraction, kg/kg
Z	number of impeller blades

Greek symbols

β	pitch of the impeller blade, deg
η	viscosity, Pa·s
φ	gas hold-up
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

g	gas phase
L	liquid phase

Dimensionless numbers

$Kg = \dfrac{\dot{V}_g}{nD^3}$	gas flow number
$M = \dfrac{g\eta_L^4(\rho_L - \rho_g)}{\sigma^3 \rho_L^2}$	Morton number
$\mathrm{Re} = \dfrac{nD^2\rho_L}{\eta_L}$	Reynolds number
$We = \dfrac{n^2D^3\rho_L}{\sigma_L}$	Weber number

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