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THE EFFECT OF VESSEL SCALE ON GAS HOLD-UP IN GAS-LIQUID SYSTEMS

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The aim of the research presented in this paper was to determine the effect of vessel scale on gas hold-up in gas-liquid systems. The agitated vessel with internal diameters of $T = 0.288$ m and $T = 0.634$ m was filled with a liquid up to the height $H = T$. For the purpose of measurements, two high-speed impellers were used: Rushton turbine impeller (RT) or A 315 impeller. Within the study, the following parameters were altered: superficial gas velocity, impeller speed, impeller type and concentration of aqueous sucrose solution. In addition, influence of the vessel scale on gas hold-up value was analysed. Experimental results were mathematically described. Equations (5)–(7) do not have equivalents in the literature.

Keywords: agitated vessel, mixing, gas hold-up, aqueous sucrose solution

1. INTRODUCTION

Mixing is one of the most important factors in chemical and biochemical processes. Vessels with one or more impellers are widely applied in various processes in chemical, food and pharmaceutical industry (Kamieński, 2004; Stręk, 1981; Vasconcelos et al., 2000). One of the most important hydrodynamic values used in the description of two-phase gas-liquid systems is the volume of gas bubbles remaining in the liquid. The efficiency of gas dispersion in the liquid influences liquid mixing, rate of heat and mass exchanged and the course of chemical and biochemical reactions undergoing in the vessels (Busciglio et al., 2017).

The contribution of gas hold-up is measured with various, less or more invasive methods. The easiest and most common is the visual method consisting in the reading of the gas-liquid mixture level increase on the vessel wall in comparison to the single-phase system. Other measurement techniques include: suction probes and image analysis, capillary suction probe, pressure or conductivity probes, laser doppler anemometry, photographic techniques, yet those require a more specialized equipment (Arjunwadkar et al., 1998; Busciglio et al., 2013; Kulkarni et al., 2011; Lee and Dudukovic, 2014; Sardeshpande et al., 2017; Takriff et al., 2009).

Gas hold-up is influenced by numerous parameters. These parameters can be divided into three main groups:

- geometric parameters – vessel and impeller diameter, height of the liquid, impeller type, number of impellers etc. (Busciglio et al., 2013; Cooke and Heggs, 2005; Cudak, 2011, 2014; Karcz and Siciarz, 2004; Khare and Niranjan, 1999, 2002; Major and Karcz, 2011; Major and Radecki, 2018; Moucha

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et al., 2003; Mueller and Dudukovic, 2010; Nocentini et al., 1993; Petricek et al., 2018, Pinelli et al., 2003; Takriff et al., 2000; Wan et al., 2016; Vasconcelos et al., 2000; Xie et al., 2014; Yawalkar et al., 2002a),

- operational parameters – impeller speed, volumetric gas flow rate etc.,
- physical parameters – surface tension of the liquid phase, density and viscosity of individual phases (Garcia-Ochoa and Gomez, 2004; Karcz and Siciarz, 2004; Karcz et al., 2004; Saravanan et al., 2009; Yawalkar et al., 2002b; Zhang et al., 2006).

Results of the impact of individual parameters on the gas hold-up have been presented in the literature in the form of different dimensional correlations $\varphi = f(n, P_g/V_L, w_{og}, \ldots)$ and dimensionless correlations $\varphi = f(\mathrm{Kg}, \mathrm{We}, \mathrm{Fr}, \ldots)$. Table 1 presents example study results.

The impeller type as well as its selection constitute the main criterion for maintaining the appropriate hydrodynamic status in the vessel in a two-phase system (Gogate et al., 2000). The Rushton turbine impeller is the most common impeller type used in the research on two-phase gas-liquid systems, as it ensures very good gas dispersion and thus good gas flow rate through the vessel (Busciglio et al., 2013; Mueller and Dudukovic, 2010; Nocentini et al.,1993; Paglianti et al., 2000; Wan et al., 2016). The disadvantage of this impeller is its high energy consumption. This impeller is characterized by a considerably higher mixing power per unit of liquid volume. Taking into account this fact, studies on two-phase gas-liquid systems began utilizing other impeller types producing radial or radial-axial liquid circulation in the vessel, typical modifications of the turbine impeller (Cooke and Heggs, 2005; Khare and Niranjan, 1999, 2002; Moucha et al. 2003; Petricek et al., 2018; Pinelli et al., 2003; Vasconcelos et al., 2000; Xie et al., 2014).

Khare and Niranje (2002) analysed the effect of impeller type on the gas hold-up. They used three impeller types in their study (standard Rushton turbine impeller and its modifications: concave bladed disc turbine, CBDT, and Scaba 6SRGT). Based on the conducted study, they determined that the highest values of gas hold-up contribution were obtained for the vessel with Rushton turbine impeller. The impact of the impeller type on the gas hold-up depended on the superficial gas velocity in the vessel and decreased with increased superficial gas velocity. Influence of the number and type of impeller on the gas hold up has been investigated by Moucha et al. (2003). They analysed the impact of 18 impeller configurations in a vessel: Rushton Turbines, six Pitched Blade impellers pumping down and hydrofoil impellers Techmix 335 pumping up or down and their configurations. The authors carried out tests in an agitated vessel with a diameter $T = 0.29$ m, in which one, two or three impellers were mounted on a common shaft. They ascertained that it was difficult to determine which configuration was the best with such a high number of variables. The study results were mathematically approximated for each configuration. The exemplary results are presented in Table 1, item 11. Vasconcelos et al. (2000) analysed the effect of different Rushton turbine impeller blade modifications on the energy consumption and gas hold up under the conditions of turbulent flow in an air-water system. They ascertained that the Rushton turbine impeller blade modification resulted in a considerable fall of mixing power. The parameter further influencing gas hold-up is the distance between impellers as well as between impellers and vessel bottom. Saravannan et al. (2009) verified that the greater the distance between impellers, the lower the values of the gas hold-up. The most favourable distance between impeller and the bottom equals $T/3$, stemming from the liquid circulation produced by the impeller. What is more, Saravannan et al. (2009) analysed the effect of physical parameters (surface tension) on the gas hold-up. They determined for an air-ethanol system that increasing the surface tension will result in reducing gas hold-up value. Influence of viscosity on the gas hold-up has been analysed by Zhang et al. (2006). The experiments were conducted for four liquids differing in viscosity: water and sugar solutions with 25, 50 and 60% concentration. Study results were presented via the equation:

$$\varphi = 0.31 \cdot n^{0.7} \cdot w_{og}^{0.52} \cdot \left(\frac{\eta_L}{\eta_w}\right)^{-0.19} \tag{1}$$

Table 1. List of equations for calculating the gas hold-up in the agitated vessel

No.	Authors	Equations	Impeller type	T, m	H/T	i	Comments
1.	Nocentini et.al., 1993	$\varphi = 8.35 \cdot 10^{-2} \cdot \left(\frac{P_g}{V_L}\right)^{0.375} \cdot w_{og}^{0.62}$	RT;	0.232	4	4	air-water;
2.	Rewatkar et al., 1993	$\varphi = 3.54 \left(\frac{D}{T}\right)^{2.08} \cdot \mathrm{Fr}^{0.51} \cdot \mathrm{Kg}^{0.43}$	PDT	0.57; 1; 1.5	1	1	air-water
3	Pinelli et al., 1994	$\varphi = 0.22 \cdot \left(\frac{P_g}{V_L}\right)^{0.215} \cdot w_{og}^{0.684}$	RT	0.48	1	1	air-water
4.	Karcz, 1998	$\varphi = 2.115 \cdot 10^{-3} \cdot \mathrm{Kg}^{0.62} \cdot \mathrm{We}^{0.64}$	RT	0.3	1	1	air-water
		$\varphi = 2.34 \cdot 10^{-4} \cdot \mathrm{Kg}^{0.51} \cdot \mathrm{We}^{1.04}$					air-glycerine
5.	Vasconcelos et al., 2000	$\varphi = 0.10 \cdot \left(\frac{P_g}{V_L}\right)^{0.37} \cdot w_{og}^{0.65}$	RT	0.392	2	2	air-water
6.	Bouaifi et al., 2001	$\varphi = a \cdot \left(\frac{P_g}{V_L}\right)^{0.24} \cdot w_{og}^{0.65}$ $a = 22.4$ for the axial configurations $a = 29.4$ for the axial mixed configurations	A 310; A 315; RT;	0.43	2	2	air-water
7.	Khare and Niranjan, 2002	$\varphi = 0.35 \cdot \left(\frac{P_g}{V_L}\right)^{0.19} \cdot w_{og}^{0.4}$	RT	0.6 m	1	1	air-1% CMC
		$\varphi = 0.53 \cdot \left(\frac{P_g}{V_L}\right)^{0.19} \cdot w_{og}^{0.49}$	CBDT				
		$\varphi = 0.8 \cdot \left(\frac{P_g}{V_L}\right)^{0.22} \cdot w_{og}^{0.57}$	Scaba				
8.	Khare and Niranjan, 2002	$\varphi = 0.071 \cdot (n)^{0.712} \cdot w_{og}^{0.36}$	RT	0.6 m	1	1	air-1% CMC
		$\varphi = 0.112 \cdot (n)^{0.68} \cdot w_{og}^{0.44}$	CBDT				
		$\varphi = 0.153 \cdot (n)^{0.73} \cdot w_{og}^{0.53}$	Scaba				

Table 1. continued

9.	Yawalkar et al., 2002a	$\varphi = 0.122\left(\frac{n}{n_{kr}}\right)^{0.64} \cdot vvm^{0.69} \cdot T^{0.22} \cdot \left(\frac{D}{T}\right)^{0.14}$	RT	0.57; 2.7	1	1	air-water
10.	Yawalkar et al., 2002b	$\varphi = 15.81 \cdot 10^{-2}\left(\frac{n}{n_{kr}}\right)^{0.734} \cdot vvm^{0.85}$	RT	0.57	1	1	air-aqueous electrolyte solutions
11.	Moucha et al., 2003	$\varphi = 0.01686 \cdot \left(\frac{P_g}{V_L}\right)^{0.6241} \cdot w_{og}^{0.5669}$	RT	0.29	1	1	0.5M Na_2SO_4 aqueous solution – pure oxygen
		$\varphi = 0.04656 \cdot \left(\frac{P_g}{V_L}\right)^{0.4666} \cdot w_{og}^{0.5816}$	PBTD				
		$\varphi = 0.04802 \cdot \left(\frac{P_g}{V_L}\right)^{0.4154} \cdot w_{og}^{0.5335}$	TXD				
12.	Karcz et al., 2004	$\varphi = \left(0.36 - 6.67 \cdot 10^{-3} \cdot x\right) \cdot \left(\frac{P_g}{V_L}\right)^{\left(0.32-2\cdot 10^{-3}\cdot x\right)} \cdot w_{og}^{\left(0.8-10^{-2}\cdot x\right)}$	RT; HE 3; A 315	0.288	2	2	air-water; air- 30% aqueous solution of glucose x = mass fraction
		$\varphi = (0.299 \cdot x - 5.8) \cdot \left(\frac{P_g}{V_L}\right)^{\left(0.07\cdot \exp\left(\frac{0.65}{10^{-2}\cdot x}\right)\right)} \cdot w_{og}^{1.1}$					air-40%, 60% or 70% aqueous solution of glucose syrup x = mass fraction
13.	Zhang et al., 2005	$\varphi = 17.2 \cdot (n)^{0.7} \cdot w_{og}^{0.52}$	RT $D/T = 0.33$	0.15	Six stages (H/T=1)	6	air-water
		$\varphi = 29.4 \cdot (n)^{0.7} \cdot w_{og}^{0.52}$	RT $D/T = 0.5$				
14.	Shewale and Pandit, 2006	$\varphi = 1.544 \cdot \left(\frac{P_g}{V_L}\right)^{0.263} \cdot w_{og}^{1.156}$	2PBTD-RT	0.3	3	3	air-water
		$\varphi = 1.504 \cdot \left(\frac{P_g}{V_L}\right)^{0.2} \cdot w_{og}^{1.079}$	3 PBTD:				

Table 1. continued

15.	Saravanan et al., 2009	$\varphi = 0.047 \cdot \left(\frac{P_g}{V_L}\right)^{0.433} \cdot w_{og}^{0.6097}$	PBTD-PBTD	0.45	2	2	air-water
		$\varphi = 0.07135 \cdot \left(\frac{P_g}{V_L}\right)^{0.4244} \cdot w_{og}^{0.6904}$	RT-RT				
16.	Major-Godlewska and Karcz, 2011	$\varphi = 3.07 \cdot 10^{-4} \cdot \mathrm{Kg}^{0.083} \cdot \mathrm{We}^{0.661} \cdot \exp\left(-0.11 \cdot \left(1 - Y^2\right)\right)$	PBTU90	0.634	1	1	air-water; air-0.4 kmol/m^3 NaCl or 0.8 kmol/m^3 NaCl $Y = 1.36$ for 0.4 kmol/m^3 NaCl $Y = 1.6$ for 0.8 kmol/m^3 NaCl
		$\varphi = 2.09 \cdot 10^{-4} \cdot \mathrm{Kg}^{0.281} \cdot \mathrm{We}^{0.761} \cdot \exp\left(-0.194 \cdot \left(1 - Y^2\right)\right)$	PBTU60				
		$\varphi = 1.69 \cdot 10^{-4} \cdot \mathrm{Kg}^{0.279} \cdot \mathrm{We}^{0.776} \cdot \exp\left(-0.22 \cdot \left(1 - Y^2\right)\right)$	PBTU45				
17.	Xie et al., 2014	$\varphi = 0.0948 \cdot \left(\frac{P_g}{V_L}\right)^{0.397} \cdot w_{og}^{0.618}$	RT	0.28	1.8	3	air-water
18.	Cudak, 2016	$\varphi = 1.478 \cdot 10^{-4} \cdot \mathrm{Kg}^{0.37} \cdot \mathrm{We}^{0.85} \cdot (1{+}150.75 \cdot c)^{0.17} \cdot (1 + 168.74 \cdot x)^{0.12}$	RT	0.634	1	1	air-water; air-1%, 2.5%, 5% or 10% aqueous solution of sucrose; $x = 0.5$ or 1% yeast suspension
		$\varphi = 1.499 \cdot 10^{-4} \cdot \mathrm{Kg}^{0.63} \cdot \mathrm{We}^{1.02} \cdot (1{+}11.66 \cdot c)^{0.47} \cdot (1 + 11.74 \cdot x)^{0.24}$	CD 6				
		$\varphi = 2.01 \cdot 10^{-4} \cdot \mathrm{Kg}^{0.49} \cdot \mathrm{We}^{0.82} \cdot (1{+}50.33 \cdot c)^{0.26} \cdot (1 + 45.56 \cdot x)^{0.11}$	A 315				
19.	Wan et al., 2016	$\varphi = 0.154 \cdot \left(\frac{P_g}{V_L}\right)^{0.41} \cdot w_{og}^{0.727}$	RT	0.29	1; 1.6	3	air-water
		$\varphi = 0.159 \cdot \left(\frac{P_g}{V_L}\right)^{0.404} \cdot w_{og}^{0.73}$					Air-Na_2SO_4 aqueous solution;
20.	Petřiček et al., 2018	$\varphi = 0.118 \cdot \left(\frac{P_g}{V_L}\right)^{0.342} \cdot w_{og}^{0.583}$	PBTD; RT; TXD	0.29; 0.59	3	1, 2, 3	Air-aqueous solution of commercial thickener “Sokrat 44”
		$\varphi = 0.688 \cdot (n \cdot D)^{0.722} \cdot w_{og}^{0.503}$					
21.	Major-Godlewska and Radecki, 2018	$\varphi = 1.41 \cdot 10^{-3} \cdot \mathrm{Kg}^{0.389} \cdot \mathrm{We}^{0.597}$	RT	0.288	2	2	air – CMC

In turn, Garcia-Ochoa and Gomez (2004) described a study of the effect of density on the contribution of the gas hold-up, using the equation:

$$\frac{\varphi}{1-\varphi} = 0.819 \cdot \frac{w_{og}^{2/3} \cdot n^{2/5} \cdot D^{4/15}}{g^{1/3}} \cdot \left(\frac{\rho_L}{\sigma}\right)^{1/5} \cdot \left(\frac{\rho_L}{\rho_L - \rho_G}\right) \cdot \left(\frac{\rho_L}{\rho_G}\right)^{-1/15} \tag{2}$$

The majority of studies presented in the literature examine the impact of different process parameters on gas hold-up in a vessel with constant dimensions. However, there are a few works in which the authors altered the vessel scale and compared the results obtained assuming constant values of other parameters e.g. variable vessel diameter (Karcz and Siciarz, 2004; Khare and Niranjan, 2004; Mueller and Dudukovic, 2010; Petricek et al., 2018; Vrabel et al., 2000).

Khare and Niranjan (2004) analysed the effect of the vessel diameter on gas hold-up. These authors showed that considerably higher values of the gas hold-up were obtained for vessels with twice larger diameter. This impact depends on the impeller speed and the superficial gas velocity. Also, Busciglio et al. (2017) analysed the influence of the vessel diameter on gas hold-up in an agitated vessel equipped with a PBT impeller. Based on the study conducted using Electrical Resistance Tomography they ascertained that the vessel scale determined characteristics of gas dispersion in the agitated vessel.

Karcz and Siciarz (2004) studied the influence of the vessel scale on the gas hold-up value. The results of the testing of the gas hold-up contribution for the data of four agitated vessels ($H = T$; $T = 0.288$ m; $H = T$; $T = 0.634$ m; $H = 2T$; $T = 0.288$ m; $H = 2T$; $T = 0.634$ m and the air – water system were described by the following relationship

$$\varphi = a\left(k_D\right) \cdot \left(\frac{P_G}{V_L}\right)^{b(k_D)} \cdot w_{og}^{c(k_D)} \tag{3}$$

where $a\left(k_D\right) = x_1 \cdot k_D + x_2$; $b\left(k_D\right) = x_3 \cdot k_D + x_4$; $c\left(k_D\right) = x_5 \cdot k_D + x_6$ are scale impact functions and $k_D = \left(\frac{T_{0.634}}{T_{0.288}}\right) \in \langle 1;\ 2.2\rangle$ is the linear coefficient of scale change (Karcz and Siciarz, 2004).

The results presented in this study aimed at determining the effect of the vessel scale on the gas hold-up in the gas-liquid systems.

2. EXPERIMENTAL

Measurements of gas hold-up were conducted in agitated vessels filled with liquid up to the height $H = T$ and using two internal diameters $T = 0.288$ m and $T = 0.634$ m. Liquid volumes of $V_L = 0.02$ m^3 and $V_L = 0.2$ m^3 were applied. Four standard baffles $B = 0.1T$ were placed in each vessel. For the purpose of the measurements, two high-speed impellers were employed differing in the type of circulation generated and the level of shear stress produced: Rushton turbine impeller (RT) or A 315 impeller. The A 315 impeller, characterised by the axial-radial liquid circulation, due to its large surface area and the shape of the blades produces low shear stress which is favourable for biological systems. The Rushton turbine impeller, with its radial-axial fluid circulation and relatively high shear stress, was selected due to its wide use in numerous processes. Detailed parameters of the vessel and impellers are presented in Fig. 1 and Tables 2 and 3.

The experiments were performed for the gas-liquid system, where air was the gas phase and aqueous sucrose solution was the liquid phase. Four aqueous sucrose solutions, several superficial gas velocities and over a dozen impeller speeds for each measurement series were tested. Table 4 presents the detailed scope of the conducted tests.

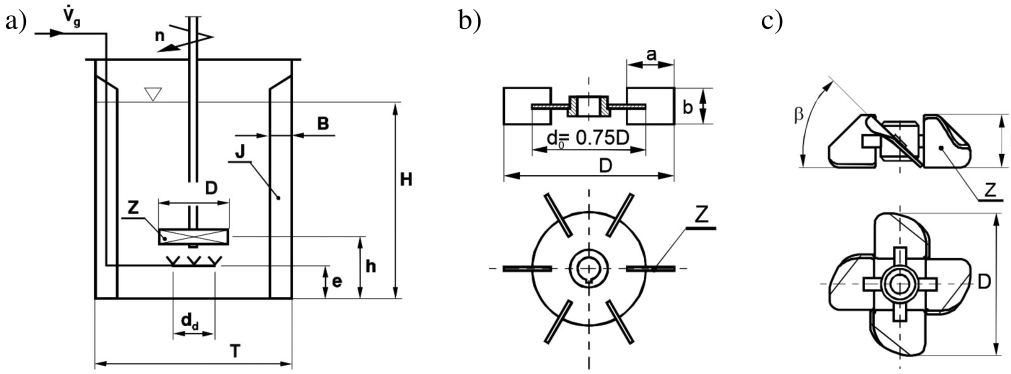

Fig. 1. Geometrical parameters of the: a) agitated vessel; b) Rushton turbine impeller (RT); c) A 315 impeller

Table 2. Geometrical parameters of vessels

No.	Geometrical parameters of vessels	Parameter values
1.	Inner vessel diameter	$T = 0.288$ m; 0.634 m
2.	Liquid height in vessel	$H = T$
3.	Number of baffles	$J = 4$
4.	Width of the baffle	$B = 0.1T$
5.	Number of impellers	$i = 1$
6.	The distance of the impeller from the bottom	$h = 0.33H$
7.	Gas sparger off-bottom clearance	$e = 0.5h$
8.	Gas sparger diameter	$d_d = 0.7T$

Table 3. Geometrical parameters of impellers

No.	Impeller	D/T	a/D	b/D	Z	β
1.	Rushton turbine (RT)	0.33	0.25	0.2	6	–
2.	A 315	0.33		0.34	4	45

Table 4. Range of the studies

Range of the studies	$T = 0.288$ m	$T = 0.634$ m
Sucrose concentration, c, %	1; 2.5; 5; 10	
Gas flow rate, V_G, m^3/s	$\langle 1.67\times10^{-4};\ 5\times10^{-4}\rangle$	$\langle 5.56\times10^{-4};\ 2.78\times10^{-3}\rangle$
Superficial gas velocity, w_{og}, m/s	$\langle 2.56\times10^{-3};\ 7.68\times10^{-3}\rangle$	$\langle 1.76\times10^{-3};\ 8.8\times10^{-3}\rangle$
Parameter, vvm (m^3/min)/m^3	$\langle 0.5;\ 1.5\rangle$	$\langle 0.16;\ 0.83\rangle$
Impeller speed, n 1/s	$\langle 7.33;\ 13.33\rangle$	$\langle 2.5;\ 6\rangle$
Gas flow number, Kg	$\langle 0.014;\ 0.071\rangle$	$\langle 0.01;\ 0.087\rangle$
Weber number, We	$\langle 593;\ 2156\rangle$	$\langle 674;\ 4521\rangle$
Specific power consumption, P_g/V_L (W/m^3)	$\langle 253;\ 4047\rangle$	$\langle 61;\ 2088\rangle$

Properties of the system changed in the following ranges: density ρ [kg/m^3] $\in \langle 1000;\ 1040\rangle$, surface tension σ [N/m] $\in \langle 0.072;\ 0.076\rangle$; dynamic viscosity η_c [Pas] $\in \langle 1\times 10^{-3};\ 1.4\times 10^{-3}\rangle$. Power consumption was measured using the strain gauge method.

The gas hold-up was calculated from the equation

$$\varphi = \frac{h_{g-c}}{h_{g-c} + H} \tag{4}$$

3. RESULTS AND DISCUSSION

Analysis of the impact of the scale of the vessel, k_D, impeller speed, n, superficial gas velocity, w_{og}, impeller type, power consumption and sucrose concentration, c, in aqueous solution on the gas hold-up in a gas-liquid system was performed based on over 1,400 measurement points.

A dependence $\varphi = f(n)$, for different systems is presented in Figs. 2–4. An influence of the impeller speed and the superficial gas velocity on the gas hold-up is shown in Fig. 2. Higher values of gas hold-up were obtained for the vessel with TR impeller than those equipped with A 315, independently of the vessel scale.

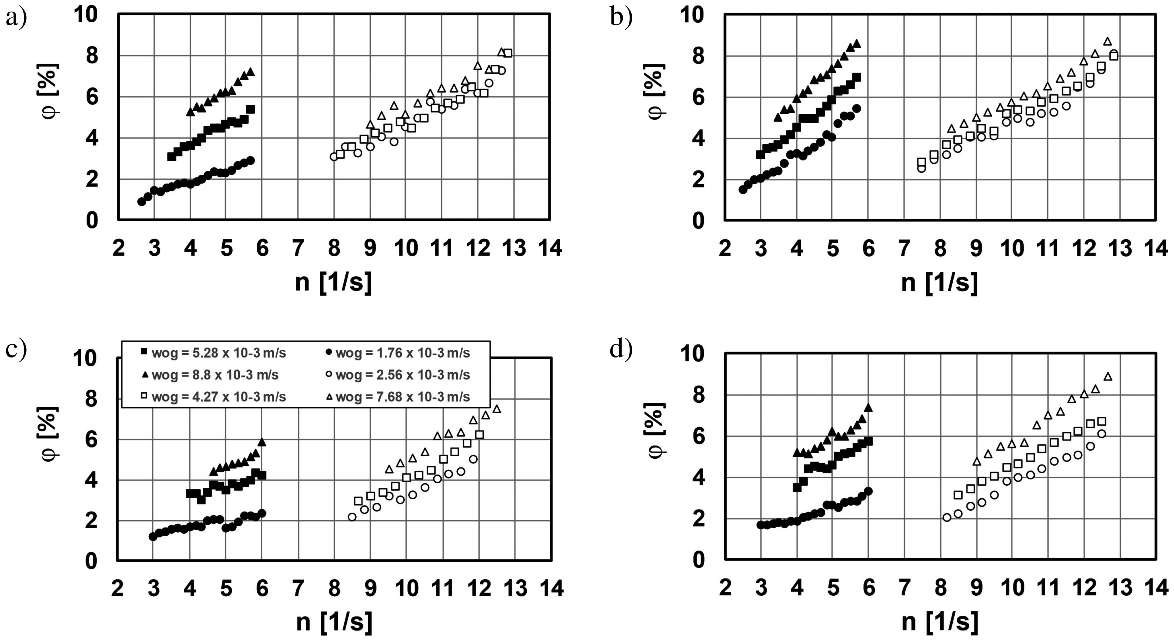

Fig. 2. The dependence $\varphi = f(n)$; a) RT; $c = 1\%$; b) RT; $c = 5\%$; c) A 315; $c = 1\%$; d) A 315; $c = 5\%$; full – $T = 0.634$ m; empty – $T = 0.288$ m

The gas-hold-up in all analysed cases increased with the increase of impeller speed n. The influence of impeller speed on the gas hold up in liquid depends on the superficial gas velocity, impeller type, sucrose concentration and vessel scale. In the case of vessel equipped with the Rushton turbine impeller, a higher (up to over 3-fold) impact of impeller speed on the gas hold-up was found. A slightly smaller effect of the impeller speed on the gas hold-up was found in the vessel equipped with the A 315 impeller. The influence of impeller speed on the gas hold-up increased with increasing viscosity in aqueous solution of sucrose (sucrose concentration in a liquid). A more pronounced impact of sucrose on the contribution of gas hold-up was found in the $T = 0.634$ m vessel. On the other hand, influence of the impeller speed on the gas hold-up decreased with the increase of the superficial gas velocity in the system. In the case of the agitated vessel with the Rushton turbine impeller, this effect relied on the vessel scale. In the vessel with

$T = 0.288$ m increasing the superficial gas velocity in the system resulted in decreased impact of impeller speed on the gas hold-up by approx. 25% while in the larger vessel by approx. 60%. In the vessel with the A 315 impeller, this effect was about 30%, independently of the vessel scale.

Gas hold-up in the all analysed cases increased also with an increasing superficial gas velocity, w_{og}. A substantially higher impact of the superficial gas velocity on gas hold-up was determined in the agitated vessel with $T = 0.634$ m. In this vessel, increasing the superficial gas velocity resulted in almost 3-fold greater gas hold-up value. The influence of superficial gas velocity on gas hold-up in the vessel with $T = 0.288$ m was lower by half. The effect of superficial gas velocity on gas hold-up also depends on the type of impeller and sucrose concentration in the system. However, in the case of impeller type, a slightly higher impact of superficial gas velocity on gas hold-up was observed for the vessel equipped with A 315 impeller than that with TR impeller. With increased sucrose concentration in the system, the influence of the superficial gas velocity on gas hold-up diminished in most cases.

Due to the different scale of vessels, the range of impeller speed for which measurements were taken differed markedly. The lowest impeller speed assumed was the speed at which good gas distribution in the liquid was observed. However, the highest speed assumed was the speed where surface aeration of the liquid in the vessel could not yet be observed. Determination at which speed comparable values of gas hold-up can be obtained independently of the vessel scale requires selecting a suitable scale-up criterion. Taterson (1994) accumulated different scale-up criteria, depending on the assumed parameters, which should be retained in both types of apparatus. These criteria can be as follows: peripheral speed at the impeller blade tip, specific power consumption, superficial gas velocity or the *vvm* parameter. The *vvm* parameter was selected as the criterion determining the impact of scale-up (Figs. 3, 4). Assuming $vvm = 0.5$ ((m^3/min)/m^3) (corresponding to $w_{og} = 2.56 \times 10^{-3}$ m/s for $T = 0.288$ m and $w_{og} = 5.27 \times 10^{-3}$ m/s for $T = 0.634$ m), obtaining comparable values of gas hold-up would require increasing (over 2-fold) the impeller speed in the $T = 0.288$ m vessel in comparison to the $T = 0.634$ m vessel. A slightly higher increase of the difference in the impeller speed in both vessels equipped with the Rushton turbine impeller was observed when the *vvm* value was increased from 0.5 (m^3/min)/m^3 to 0.83 (m^3/min)/m^3. For this impeller, at higher

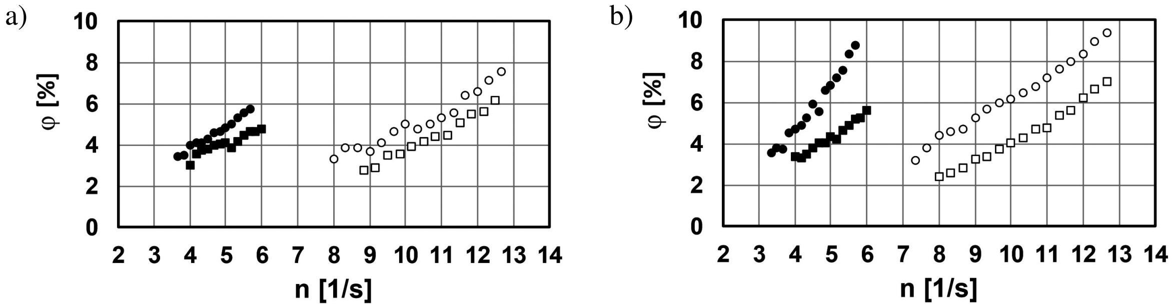

Fig. 3. The dependence $\varphi = f(n)$; *vvm* = 0.5 (m^3/min)/m^3; a) $c = 2.5\%$; b) $c = 10\%$; full – $T = 0.634$ m; empty – $T = 0.288$ m; square – A 315; circle – TR

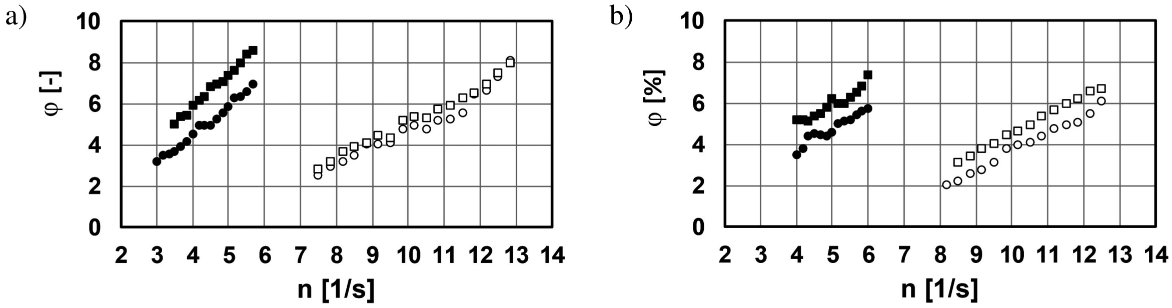

Fig. 4. The dependence $\varphi = f(n)$; a) TR; b) A 315; $c = 5\%$; full – $T = 0.634$ m; empty – $T = 0.288$ m; circle – *vvm* = 0.5 (m^3/min)/m^3; square – *vvm* = 0.83 (m^3/min)/m^3

vvm values, obtaining comparable values of gas hold-up would require increasing the impeller speed by approximately 2.5 times in the $T = 0.288$ m vessel.

Influence of the vessel scale, k_D $\left(k_D = \left(\frac{T_{0.634}}{T_{0.288}}\right) \in \langle 1; 2.2\rangle\right)$, impeller speed, n, volumetric gas flow rate, *vvm*, and concentration of aqueous sucrose solution, c, on φ gas hold-up can be described mathematically by means of the following equation:

$$\varphi = x_1 \cdot n^{x_2} \cdot vvm^{x_3} \cdot (1+c)^{x_4} \tag{5}$$

The functions x_1, x_2, x_3, x_4 in Eq. (5) are listed in Table 5.

Table 5. Functions x_1, x_2, x_3, x_4 in Eq. (5)

Impeller	RT	A 315
x_1	$-4.556 \times 10^{-3} \cdot k_D + 0.011$	$-6.909 \times 10^{-3} \cdot k_D + 0.016$
x_2	$0.306 \cdot k_D + 1.089$	$0.599 \cdot k_D + 0.521$
x_3	$-0.214 \cdot k_D + 0.582$	$-0.164 \cdot k_D + 0.689$
x_4	$-2.126 \cdot k_D + 6.888$	$-0.031 \cdot k_D + 2.452$
$+\Delta$	8%	8%

In terms of the tank scale, the results of power consumption dependence on the *vvm* parameter were also analysed. The relationship $P_g/V_L = f(n)$ is shown in Fig. 5. Assuming *vvm* = const, it was found that the specific power consumption P_g/V_L in both vessels was achieved at about 1.6 times higher impeller speed in the small agitated vessel. The value of *vvm* = const corresponds to about twice the value of w_{og} in the small vessel compared to that in the large vessel.

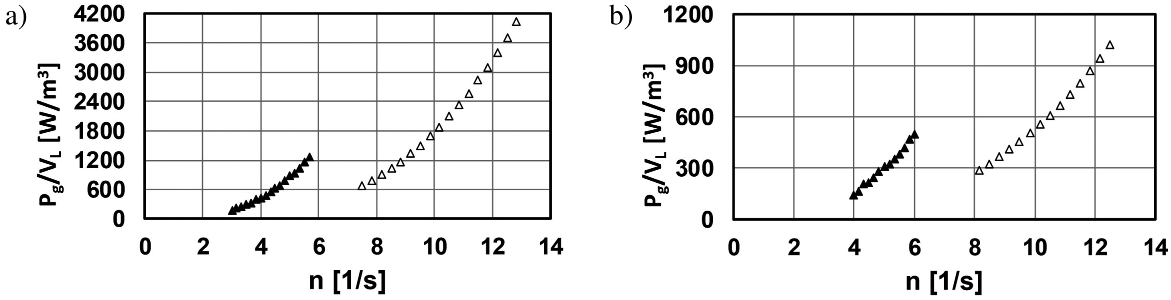

Fig. 5. The dependence $P_g/V_L = f(n)$; $vvm = 0.5$ (m^3/min)/m^3; $c = 5\%$; a) TR; b) A 315;
full – $T = 0.634$ m; empty – $T = 0.288$ m

A relationship $\varphi = f(P_g/V_L)_{vvm=\text{const}}$ for tanks differing 10-fold in volume of liquid is presented in Fig. 6. Assuming a constant P_g/V_L value, the gas hold-up for a tank with a diameter of $T = 0.634$ m is about 1.4 times higher compared to the values obtained in a tank with a diameter of $T = 0.288$ m. However, to obtain a comparable gas hold-up value, assuming *vvm* = const, the specific power consumption P_g/V_L in the small tank ($T = 0.288$ m) will be from 1.5 to even more than 3 times higher than that in the large tank ($T = 0.634$ m). The impact of the tank scale increases with increasing *vvm*.

The influences of the vessel scale, k_D, specific power consumption, P_g/V_L, superficial gas velocity, w_{og}, and aqueous sucrose solution concentration, c, on gas hold-up φ were approximated in the form of the following equation:

$$\varphi = x_1 \cdot \left(\frac{P_g}{V_L}\right)^{x_2} \cdot w_{og}^{x_3} \cdot (1+c)^{x_4} \tag{6}$$

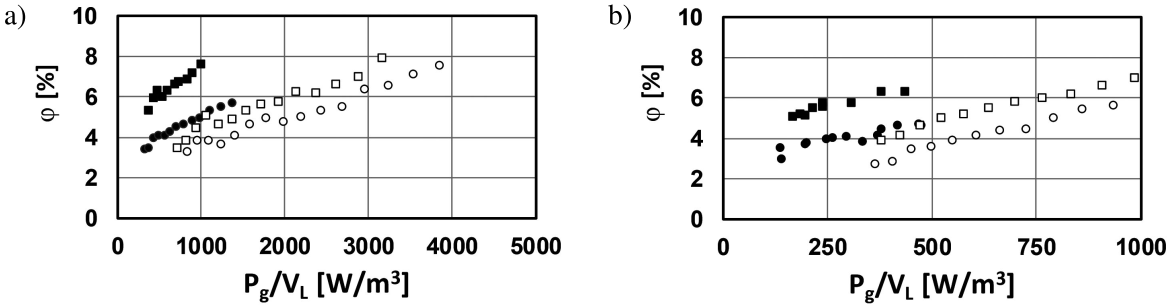

Fig. 6. The dependence $\varphi = f(P_g/V_L)$; $c = 2.5\%$; a) TR; b) A 315; full – $T = 0.634$ m; empty – $T = 0.288$ m; circle – $vvm = 0.5$ (m^3/min)/m^3; square – $vvm = 0.83$ (m^3/min)/m^3

The functions x_1, x_2, x_3, x_4 in Eq. (6) are listed in Table 6.

Table 6. Functions x_1, x_2, x_3, x_4 in Eq. (6)

Impeller	RT	A 315
x_1	$-0.037 \cdot k_D + 0.092$	$-0.108 \cdot k_D + 0.256$
x_2	$0.054 \cdot k_D + 0.381$	$-0.195 \cdot k_D + 0.132$
x_3	$-0.17 \cdot k_D + 0.768$	$-0.107 \cdot k_D + 0.714$
x_4	$-2.126 \cdot k_D + 6.888$	$-0.031 \cdot k_D + 2.452$
$+\Delta$	8%	8%

The distribution of gas hold-up as the function of a number of gas flow Kg, for different systems, is presented in Figs. 7, 8. Influence of the gas flow number on gas hold-up depends on the vessel scale.

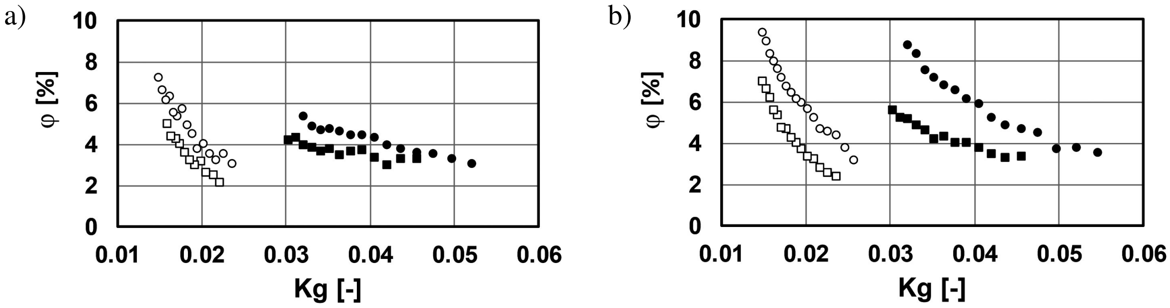

Fig. 7. The dependence $\varphi = f(\mathrm{Kg})$; a) $c = 1\%$; b) $c = 10\%$; $vvm = 0.5$ (m^3/min)/m^3; full – $T = 0.634$ m; empty – $T = 0.288$ m; square – A 315; circle – RT

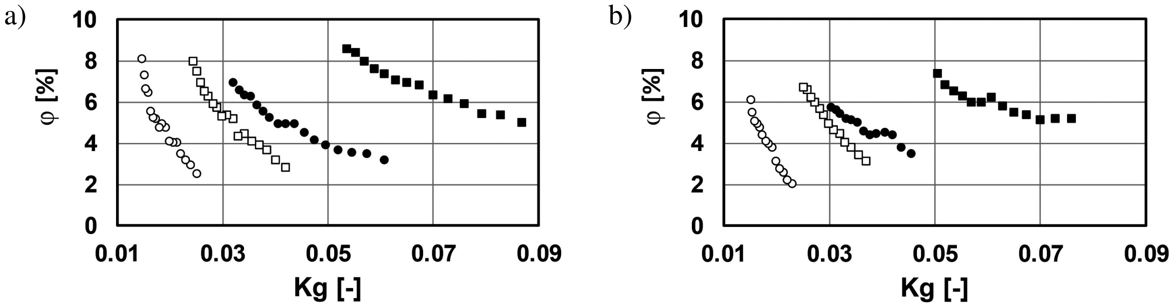

Fig. 8. The dependence $\varphi = f(\mathrm{Kg})$; a) RT; b) A 315; $c = 5\%$; full – $T = 0.634$ m; empty – $T = 0.288$ m; square – $vvm = 0.83$ (m^3/min)/m^3; circle – $vvm = 0.5$ (m^3/min)/m^3

A more pronounced impact was observed in the $T = 0.288$ m vessel. This effect decreased with increased *vvm*. Assuming a constant $vvm = 0.5$ (m^3/min)/m^3, higher values of gas hold-up, independently of the gas flow number Kg, were obtained for agitated vessel with Rushton turbine impeller. The effect of impeller type on gas hold-up increased with increased concentration of sucrose in the system. For the $T = 0.288$ m vessel, assuming Kg = const, increasing the aqueous sucrose solution concentration from 1% w/w to 10% w/w resulted in over 2-fold increase of the impeller impact on gas hold-up. This effect did not rely on the gas flow number Kg. On the other hand, the influence of the impeller type on gas hold-up in the $T = 0.634$ m vessel was strongly dependent on the gas flow number Kg. Influence of the impeller type on gas hold-up decreased with increased gas flow number Kg.

Assuming constant gas flow number value Kg, gas hold-up increased with increasing *vvm*. Increasing the *vvm* value from 0.5 (m^3/min)/m^3 to 0.83 (m^3/min)/m^3 independently of the impeller type and vessel scale resulted in increasing gas hold-up by up to over 2-fold.

Comparable values of gas hold-up in two vessels with different size can be obtained at different values of the gas flow number Kg. For the $T = 0.634$ m agitated vessel, comparable values of gas hold-up obtained in the $T = 0.288$ m vessel would be obtained at markedly higher Kg values. The *vvm* value determined the degree to which the gas flow number had to be increased in order to obtain comparable gas hold-up values. For $vvm = 0.5$ (m^3/min)/m^3, comparable gas hold-up values would be obtained for the larger vessel by increasing the gas flow number by about 2-fold, whereas for $vvm = 0.83$ (m^3/min)/m^3 these values shall be increased by 2.5-fold.

An influence of the vessel scale, k_D, gas flow number, Kg, Weber number and aqueous sucrose solution concentration, c, on gas hold-up, φ, can be described as follows:

$$\varphi = x_1 \cdot \mathrm{Kg}^{x_2} \cdot \mathrm{We}^{x_3} \cdot (1 + c)^{x_4} \tag{7}$$

The expressions for x_1, x_2, x_3, x_4 in Eq. (7) are listed in Table 7.

Table 7. Functions x_1, x_2, x_3, x_4 in Eq. (7)

Impeller	RT	A 315
x_1	$-3.148 \times 10^{-5} \cdot k_D + 1.60210^{-4}$	$-1.868 \times 10^{-4} \cdot k_D + 4.691 \times 10^{-4}$
x_2	$-0.214 \cdot k_D + 0.582$	$-0.163 \cdot k_D + 0.689$
x_3	$0.045 \cdot k_D + 0.836$	$0.217 \cdot k_D + 0.607$
x_4	$-2.126 \cdot k_D + 6.888$	$-0.031 \cdot k_D + 2.452$
$+\Delta$	8%	8%

Taking into account different ranges of the physical and geometrical factors used in investigations of gas hold-up reported in literature, it is difficult to analyse closely these results. However, experimental data of gas hold-up presented in this study are compared with the data of other authors (Fig. 9). Curves 1, 2, 3, 4 concern Newtonian liquid phase and curve 5 describes non-Newtonian liquid phase. Curves 1, 2, 3, 5 correspond to a coalescing gas-liquid system and curve 4 – to a non-coalescing system. As predicted, higher values of gas hold-up for the agitated vessel with the same inner diameter ($T = 0.29$ m) characterise the non-coalescing system (curves 1 and 4). It is worth noticing that the results (curve 1) include a very wide range of the specific power consumption P_g/V_L. As shown in Fig. 9, rheological properties of the liquid phase have a significant effect on gas hold-up (curves 5 ($T = 0.6$ m) and 2 ($T = 0.634$ m)).

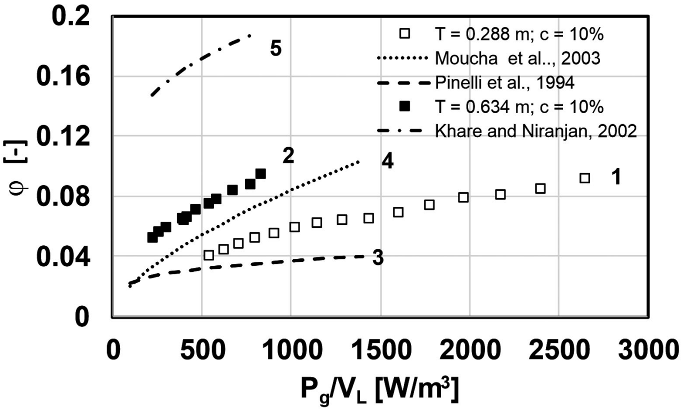

Fig. 9. The dependence $\varphi = f(P_g/V_L)$; RT; w_{og} = 0.008 m/s; 1 – air-water; T = 0.48 m; 2 – 10% aqueous solution of sucrose; T = 0.288 m; 3 – pure oxygen-0.5M Na_2SO_4; T = 0.29 m; 4 – 10% aqueous solution of sucrose; T = 0.634 m; 5 – air-1% CMC; T = 0.6 m

4. CONCLUSIONS

As a result of testing gas hold-up in vessels with different volume, a wide, uniform database has been created, including approximately 1400 experimental points. It comprised the basis for the assessment of impact of selected parameters, including the vessel scale on gas hold-up. The selected scope of scale change included two vessels with ten-fold difference in liquid volume. The conducted study revealed that a consistent determination of the effect of the given parameter on gas hold-up is a very difficult task. Whether a given value results in an increase or a decrease of gas hold-up can roughly be assessed, yet determination to what extent it depends on other parameters. For instance, gas hold-up in all the analysed cases increased with increased impeller speed. However, the level of the increase depended on the vessel scale, impeller type, sucrose concentration or superficial gas velocity in the system. Furthermore, analysis of the obtained results allowed to verify the order in which individual parameters influenced gas hold-up. The greatest effect on gas hold-up was exerted by impeller speed and superficial gas velocity, while the lowest by the sucrose concentration in aqueous solutions. In order to achieve comparable values of gas hold-up in two agitated vessels of different size, the impeller speed should be increased over 2-fold.

SYMBOLS

A	length of impeller blade, m
B	width of the baffle, m
b	width of impeller blade, m
c	sucrose concentration, % mass
D	diameter of the impeller, m
d_d	sparger diameter, m
d_o	diameter of impeller disc, m
e	off-bottom clearance of gas sparger, m
H	liquid height in the vessel, m
H	distance between impeller and bottom of the vessel, m
h_{g-c}	the height of a gas-liquid mixture in the agitated vessel, m
i	number of impellers
J	number of baffles
n	impeller speed, 1/s

P_g/V_L	specific power consumption, W/m^3
T	inner diameter of the agitated vessel, m
V_L	volume of the liquid in the vessel, m^3
V_g	gas flow rate, m^3/s
w_{og}	superficial gas velocity, $= \frac{4\dot{V}_g}{\pi D^2}$, m/s
vvm	volume of gas sparged per unit volume of the liquid per minute, (m^3/min^{-1})/m^3
Z	number of impeller blades

Greek symbols

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

Subscripts

G	refers to gas phase
L	refers to liquid phase

Dimensionless numbers

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

Fr $= \dfrac{n^2 d}{g}$ Froude number

Re $= \dfrac{nd^2\rho_L}{\eta_L}$ Reynolds number

We $= \dfrac{n^2 d^3 \rho_L}{\sigma_L}$ Weber number

Acronyms

CBDT	concave blade disk turbine
CD 6	Smith turbine
PBTD	pitched blade turbine down- pumping
PBTU	pitched blade turbine up- pumping
RT	Rushton turbine
TXD	hydrofoil impeller up-pumping

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