Gas Hold-Up in a Reactor with Dual System of Impellers*

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Dedicated to the 80th birthday of Professor Elemír Kossaczký

Results of experimental studies of gas hold-up in a liquid stirred mechanically in a reactor, which was equipped with double stirrers on a common shaft, are presented. Coalescing and noncoalescing gas—liquid systems were tested. The measurements were carried out for aqueous solutions of glucose and glucose sirup, as well as for different configurations of dual high-speed impellers. Stirred tank with inner diameter $D = 0.288$ m was filled with a liquid up to the height $H = 2D$. Experimental studies of gas hold-up in the coalescing and noncoalescing gas—liquid systems stirred using dual system of high-speed impellers show that gas hold-up φ for the noncoalescing systems is considerably higher than that for the coalescing ones. The configuration of dual system of impellers used in the study slightly affects only gas hold-up and this effect can be neglected. The dependence of gas hold-up φ on the specific power consumption P_g/V_L and superficial gas velocity w_{og} for coalescing and noncoalescing systems can be described by means of eqns (*2*) and (*3*), respectively.

Problem of the unequal distribution of the gas bubbles (oxygen concentration) in a liquid can be overcome using mechanical stirring, which intensifies processes in a bioreactor. Presence of oxygen diluted in the liquid is limiting for the growth of microorganisms and efficiency of the bioreaction. The aeration intensity could be insufficient in the case of the biosynthesis processes, where mass transfer is slow. The process can be accelerated providing energy by means of stirrers.

In the case of reactors used for stirring the gas—liquid systems, tall tanks are recommended in order to improve utilization of the gas phase introduced into the stirred tank. One of possible arrangements could be a system of impellers on a common shaft operating in such tank [1, 2]. In bioreactors equipped with double impellers, the regions of sufficient gas dispersion arise in the vicinity of stirrers, where the gas bubbles have the lowest dimensions.

The amount of gas in the gas—liquid system may be assumed as the simplest measure of the effectiveness of the gas dispersion by means of a stirrer. The gas loading in liquid depends on many factors, such as: intensity of stirring, geometrical parameters of the tank and stirrer, the stirrer type, as well as the gas—liquid system properties [3—5]. Several groups of authors studied the gas hold-up in stirred tanks [6—16], *e.g.* *Barigou* and *Greaves* [8] and *Bombac* and *Zun* [9] measured local values of the gas hold-up. The latter authors deal with the recognition of the different gas-filled cavity structures close to the impeller blade, which were formed in the pilot-size stirred tank equipped with dual *Rushton* turbines. *Majirova et al.* [10] analyzed the gas behaviour in a tank with triple impellers, employing the RTD and axial dispersion model. Coalescing and noncoalescing systems were stirred using down- or up-pumping pitched blade turbines. *Linek et al.* [11] conducted measurements in the tanks equipped with four stirrers on a common shaft. Further, *Kamieński* and *Niżnik* [12—14] performed multipurpose studies in stirred tanks within a wide range of variables. The effects of the shape of impeller blade on the gas hold-up and the volumetric mass transfer coefficient for aerated stirred tank with dual radial flow impellers were experimentally investigated by *Orvalho et al.* [15]. The results obtained for five modified types of the *Rushton* turbine showed that all the impellers provided the same gas hold-up and mass transfer coefficient at the same power consumption and superficial gas velocity. Taking into account scale-up aspect, the effects of the type of stirrer and different configurations of double impellers on a common shaft on the power consumption and gas hold-up

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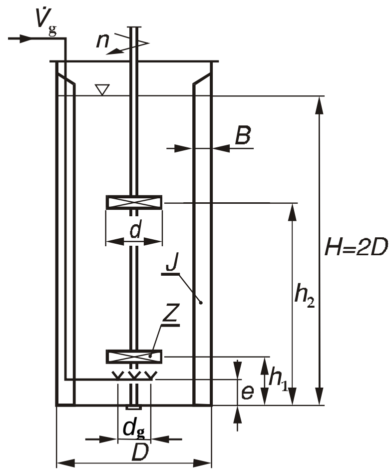

Fig. 1. Geometrical parameters of the stirred tank with dual system of impellers.

were studied by *Karcz et al.* [16]. The authors [16] analyzed the systems with the different lower high-speed impellers, which operated in the tanks differing ten times within the liquid volume.

The results of an experimental study of gas hold-up in the liquid in a mechanically stirred reactor equipped with double stirrers on a common shaft are presented in the paper. Coalescing and noncoalescing gas—liquid systems were investigated. The measurements were carried out for aqueous solutions of glucose and glucose sirup, as well as for different configurations of dual high-speed impellers. An effect of the different liquid pumping modes of the upper stirrer on the gas hold-up was analyzed.

EXPERIMENTAL

Measurements were carried out in a tall, cylindrical reactor with inner diameter $D = 0.288$ m (Fig. 1). Liquid level in the vessel was equal to $H = 2D$. The vessel with transparent walls had flat bottom and four

Table 1. Geometrical Parameters of the Stirrers Used

	Stirrer	d/D	a/d	b/d	Z	$\beta/°$
1	*Rushton* turbine (TR)	0.33	0.25	0.2	6	
2	A 315	0.33		0.4	4	45
3	Propeller, $S/d = 1$	0.33		0.2	3	
4	HE 3	0.33		0.19	3	30

planar baffles with the width $B = 0.1D$. Two impellers with diameter $d = 0.33D$ were located at the distance $h_1 = 0.17H$ and $h_2 = 0.67H$ from the bottom of the tank, respectively. Four configurations of impellers imposing different liquid circulation in the vessel were tested (Table 1). During all experiments *Rushton* disc turbine was placed at the lower position. As upper stirrer *Rushton* turbine, propeller, HE 3, or A 315 impellers were used (Fig. 2). Ring-shaped gas sparger with diameter $d_g = 0.7d$ was placed under lower impeller at the distance $e = 0.5d$ from the bottom of the tank.

Air—liquid systems with varying physical properties of the continuous phase were stirred (Table 2). The experiments were conducted for the following liquid phase: distilled water, aqueous solution with glucose mass fraction $x = 30$ %, and for aqueous solutions with glucose sirup mass fraction $x = 40$ %, 60 %, or 70 %. Physical parameters of these liquids were varied within the following range: density $\rho_L/(\text{kg m}^{-3}) \in \langle 1000; 1258\rangle$; viscosity $\eta_L/(\times 10^3 \text{ Pa s}) \in \langle 1; 32.5\rangle$, and surface tension $\sigma/(\text{N m}^{-1}) \in \langle 0.072; 0.095\rangle$. Systems comprising water or glucose characterize the capability to coalesce gas bubbles. Systems with glucose sirup behave as noncoalescing systems.

Gas hold-up measurements were carried out for varying stirrer speeds n. As the lower limit, the stirrer speed was assumed, at which the gas dispersion under the lower impeller was observed. Gas flow rate $\dot{V}_g$ was changed within the range up to 3.32×10^{-4} m^3 s^{-1}, corresponding to superficial gas velocity of $w_{og} = 5.1$

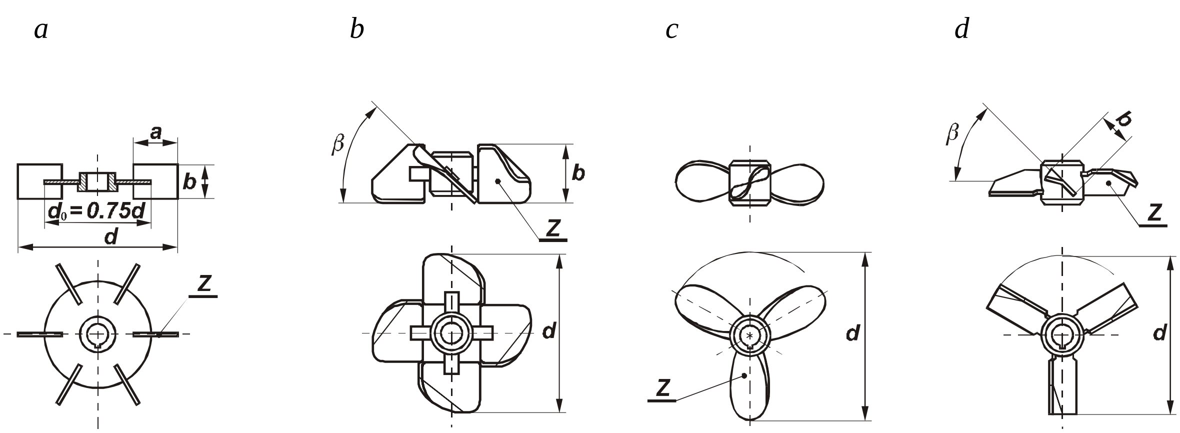

Fig. 2. Types of stirrers used: *a*) *Rushton* turbine; *b*) A 315; *c*) propeller; *d*) HE 3.

Table 2. Properties of Liquids at a Temperature of 20 °C

	Liquid	ρ_L / kg m^{-3}	$\eta_L \times 10^3$ / Pa s	$\sigma \times 10^3$ / N m^{-1}	Capability to coalesce
1	Distilled water	1000	1	72	+
2	30 % aqueous solution of glucose	1200	3.0	72.4	+
3	40 % aqueous solution of glucose sirup	1137	3.6	74	–
4	60 % aqueous solution of glucose sirup	1210	13.6	79.5	–
5	70 % aqueous solution of glucose sirup	1258	32.5	95.2	–

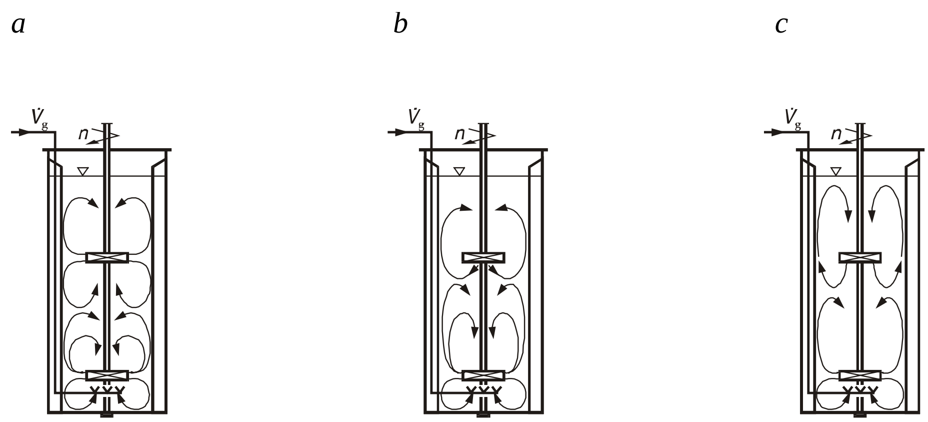

Fig. 3. Circulation loops in the stirred tank equipped with dual system of impellers on a common shaft: *a*) double *Rushton* turbines; *b*) lower impeller: *Rushton* turbine, upper: A 315; *c*) lower impeller: *Rushton* turbine, upper: HE 3.

$\times\ 10^{-3}$ m s^{-1} (where $w_{og} = 4\dot{V}_g/\pi D^2$). Gas hold-up, φ, was calculated from the following equation

$$\varphi = \frac{V_g}{V_g + V_L} = \frac{h_g}{h_g + H} \qquad (1)$$

where V_g and V_L denote volumes of gas and liquid in the stirred tank, while $h_g = H_g - H$ corresponds to the difference between the height of gas—liquid mixture, H_g, and the height of liquid in the tank, H. The values of h_g were read about 20 times from the scale located on the cylindrical wall of the tank. Averaged value of the gas hold-up was used for further calculations.

Circulation loops within the tank equipped with the systems of impellers are shown in Fig. 3. Fig. 3*a* illustrates the liquid circulation in the tank equipped with double *Rushton* turbines, where four radial loops are generated. The variant with the upper A 315 impeller is presented in Fig. 3*b*. In this case, characteristic down-pumping liquid circulation is observed in the upper part of the tank. Liquid circulation imposed by the system composed of the lower radial flow *Rushton* turbine and upper axial flow HE 3 impeller is shown in Fig. 3*c*. Upper loops formed by the downwards pumping HE 3 impeller are more regular and elongated in comparison with those generated by A 315 impeller.

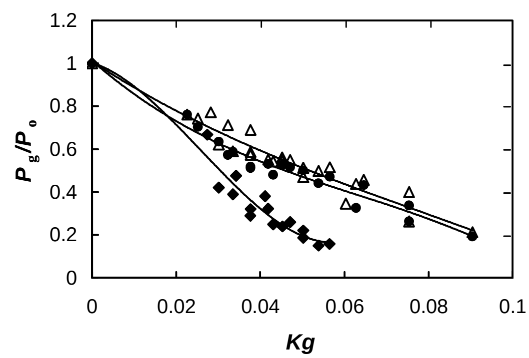

Fig. 4. Experimental (symbols) and fitted (lines) relative power consumption values obtained for the system air—distilled water stirred with two impellers on a common shaft. Lower impeller: *Rushton* turbine; upper impellers: △ *Rushton* turbine, ● A 315, or ◆ HE 3.

RESULTS AND DISCUSSION

Presence of a gas phase in mechanically stirred liquid affects significantly the power consumption. Power consumption of a gas—liquid system, P_g, depending also on the impeller type and the mutual location of stirrers on the common shaft, is usually related to the power consumption of the liquid phase, P_o. For example, the power characteristics representing variation of the relative power consumption P_g/P_o with gas flow number Kg for air-distilled water system and different configurations of impellers are shown in Fig. 4. The values of the P_g/P_o decreased dramatically with the gas flow number increase. Higher drop of the rel-

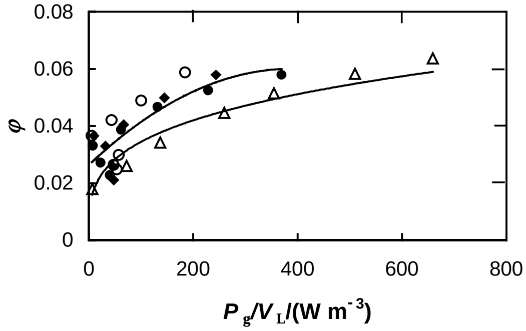

Fig. 5. Experimental (symbols) and fitted (lines) gas hold-up values obtained for the system air—30 % glucose solution in distilled water stirred with two impellers on a common shaft at $w_{og} = 5.2 \times 10^{-3}$ m s^{-1}. Lower impeller: *Rushton* turbine; upper impellers: △ *Rushton* turbine, ● A 315, ○ propeller, or ◆ HE 3.

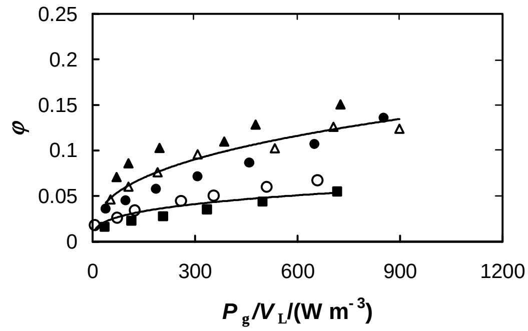

Fig. 7. Experimental (symbols) and fitted (lines) gas hold-up values obtained for the system gas—liquid stirred with two *Rushton* turbines on a common shaft at $w_{og} = 5.2 \times 10^{-3}$ m s^{-1}. Gas: air; liquids: ■ distilled water, ○ 30 % glucose solution in distilled water, and △ 40 %, ▲ 60 %, or ● 70 % glucose sirup solution in distilled water.

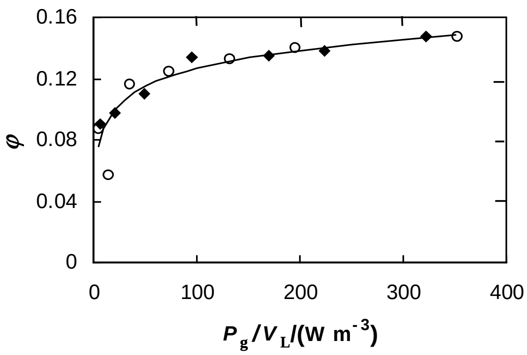

Fig. 6. Experimental (symbols) and fitted (line) gas hold-up values obtained for the system air—60 % glucose sirup solution in distilled water stirred with two impellers on a common shaft at $w_{og} = 5.2 \times 10^{-3}$ m s^{-1}. Lower impeller: *Rushton* turbine; upper impellers: ○ propeller or ◆ HE 3.

ative power consumption was observed in the case of dual stirring system with axial flow impeller (HE 3 impeller) in the upper position.

The dependence of gas hold-up, φ, on the specific power consumption, P_g/V_L, can be estimated on the basis of the results of power consumption measurements for gas—liquid system. The course of the function $\varphi = f(P_g/V_L)$ for given superficial gas velocity, w_{og}, different configurations of double impellers on the common shaft, and for gas—liquid systems with different capability to coalesce gas bubbles is shown in Figs. 5—7. Fig. 5 illustrates the results obtained for the coalescing system air—aqueous solution of glucose containing 30 % of this saccharide. In this case, slight effect of the impeller type on the gas hold-up reveals. The data measured for the system comprising double *Rushton* turbines lie slightly below the points obtained for the other configurations of impellers. The conclusion concerning just a small effect of the impeller type on the gas hold-up agrees with the previously published results [15]. *Orvalho et al.* [15] found the gas hold-up approximately independent of the impeller type at a given power consumption and superficial gas velocity, taking into account an error of experimental data.

The dependence $\varphi = f(P_g/V_L)$ for the noncoalescing system air—glucose sirup solution containing 60 % of glucose sirup, stirred using the dual system of stirrers with the axial flow impeller as the upper one, is shown in Fig. 6. In this case, the gas hold-up practically did not depend on the impeller type and its values were significantly higher than those, obtained for the coalescing gas—liquid systems (*e.g.* Fig. 5). The effect of the liquid capability to coalesce gas bubbles on the gas hold-up is shown in Fig. 7, where the results observed for double *Rushton* turbines at a given superficial gas velocity $w_{og} = 5.2 \times 10^{-3}$ m s^{-1} and five different gas—liquid systems are presented.

The experimental points in Fig. 7 can be divided into two groups. The first one includes the data measured for distilled water and aqueous solution of glucose as continuous phase, whilst the solutions of glucose sirup represent the second group. The effect of the capability of liquid phase to coalesce gas bubbles on gas hold-up is considerable, as the volume of gas phase held in the liquid was two times bigger for noncoalescing systems compared to the gas hold-up in coalescing liquids.

As the influence of stirrers configuration on the gas hold-up was negligible compared to the effect of liquid properties, the experimental gas hold-up values were fitted using the function $\varphi = f(P_g/V_L,\ w_{og}) = const1(P_g/V_L)^{const2}(w_{og})^{const3}$. Exponents ($const2$ and $const3$) and coefficient $const1$ varied, depending on the capability to coalesce gas bubbles and concentration of the solution. For coalescing gas—liquid systems (air—distilled water, air—aqueous solution of

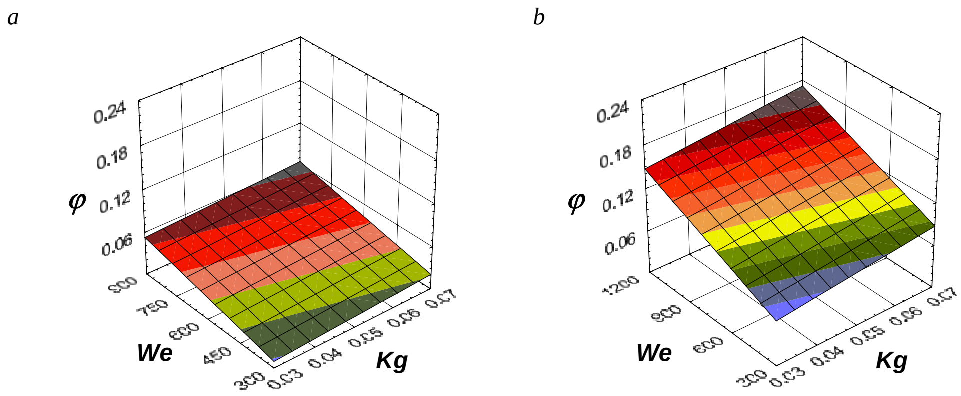

Fig. 8. Gas hold-up variation with Kg and We for the systems: *a*) air—distilled water, and *b*) air—60 % glucose sirup solution in distilled water, stirred with double *Rushton* turbines.

glucose) the following equation was obtained

$$\varphi = \left(0.36 - 6.67\times10^{-3}x/\%\right)\left(\frac{P_\mathrm{g}}{V_\mathrm{L}}\right)^{\left(\alpha-2\times10^{-3}x/\%\right)} \cdot \cdot\, w_\mathrm{og}^{\left(\gamma-10^{-2}x/\%\right)} \qquad (2)$$

where $\alpha = 0.32$, $\gamma = 0.8$, x denotes glucose mass fraction within the range $0 < x/\% < 30$; specific energy $P_\mathrm{g}/V_\mathrm{L} < 900$ W m^{-3}; and superficial gas velocity $w_\mathrm{og} \leq 5.2\times10^{-3}$ m s^{-1}.

For noncoalescing gas—liquid systems (air—glucose sirup systems) one gets

$$\varphi = (0.299x/\% - 5.8)\left(\frac{P_\mathrm{g}}{V_\mathrm{L}}\right)^{\left(0.07\cdot\exp\left(\frac{0.65}{10^{-2}x/\%}\right)\right)} w_\mathrm{og}^{1.1} \qquad (3)$$

where x indicates glucose sirup mass fraction within the range $40 < x/\% < 70$; specific energy $P_\mathrm{g}/V_\mathrm{L} < 400$ W m^{-3}; and superficial gas velocity $w_\mathrm{og} \leq 5.2\times10^{-3}$ m s^{-1}.

Eqns (*2*) and (*3*) approximate the experimental data with maximum relative error of 25 %, but the mean relative errors are smaller and equal to 12 % and 15 %, respectively.

Values of parameters α and γ in eqn (*2*) are in reasonable agreement with the data proposed for different configurations of multiple impellers and the system air—distilled water. *Orvalho et al.* [15] reported $\alpha = 0.37$ and $\gamma = 0.65$ for double modified *Rushton* turbines. *Majirova et al.* [10] found $\alpha = 0.24$—0.29 and $\gamma = 0.51$—0.67 for triple pitched blade turbines.

For comparative purposes, variation of the gas hold-up in liquids with different properties is presented in Fig. 8 in a form of function $\varphi = f(Kg, We)$. Within the range of the experiments carried out during this study, the gas hold-up of noncoalescing systems (Fig. 8*b*) is two or three times the value measured for coalescing liquids (Fig. 8*a*).

SYMBOLS

a	length of impeller blade	m
b	width of impeller blade	m
B	width of the blade	m
d	impeller diameter	m
d_g	diameter of a gas sparger	m
D	inner diameter of stirred tank	m
e	distance between the gas sparger and the bottom of the tank	m
h_1	distance between the lower impeller and the tank bottom	m
h_2	distance between the upper impeller and the tank bottom	m
h_g	difference between the level of gas—liquid system and liquid in the tank	m
H	liquid level in the tank	m
H_g	level of gas—liquid system in the tank	m
i	number of impellers on the common shaft	
J	number of baffles	
Kg	gas flow number ($= \dot{V}_\mathrm{g}/nd^3$)	
n	stirrer speed	s^{-1}
P_g	power consumption for gas—liquid system	W
P_o	power consumption for liquid phase	W
S	propeller pitch	m
V_g	gas volume in the liquid	m^3
$\dot{V}_\mathrm{g}$	gas flow rate	m^3 s^{-1}
V_L	liquid volume in the tank	m^3
We	Weber number ($= n^2d^3\rho_\mathrm{L}/\sigma$)	
w_og	superficial gas velocity ($= 4\dot{V}_\mathrm{g}/\pi D^2$)	m s^{-1}
x	mass fraction	
Z	number of impeller blades	
α	adjustable parameter in eqn (*2*)	
β	pitch of the impeller blade	°
γ	adjustable parameter in eqn (*2*)	
η_L	liquid viscosity	Pa s
φ	gas hold-up defined by eqn (*1*)	
ρ_L	liquid density	kg m^{-3}
σ	surface tension	N m^{-1}

REFERENCES

1. Stręk, F., *Agitation and Agitated Vessels* (in Polish). Wydawnictva Naukovo-Techniczne, Warsaw, 1981.
2. Schuegerl, K. and Bellgardt, K. H., *Bioreaction Engineering. Modeling and Control*. Springer-Verlag, Berlin, 2000.
3. Karcz, J., *Inż. Chem. Proc. 19*, 335 (1998).
4. Karcz, J., *Inż. Ap. Proc. 41*, 1 (2002).
5. Bombac, A. and Zun, I., *J. Mech. Eng. 48*, 663 (2002).
6. Warmoeskerken, M. M. C. G., *Thesis.* TU, Delft, 1986.
7. Murugesan, T. and Degeleesan, T. E., *Chem. Eng. Commun. 117*, 263 (1992).
8. Barigou, M. and Greaves, M., *Trans. Inst. Chem. Eng., Part A 74*, 397 (1996).
9. Bombac, A. and Zun, I., *Chem. Eng. Sci. 55*, 2995 (2000).
10. Majirova, H., Pinelli, D., Machon, V., and Magelli, F., *Preprints of the 11th European Conference on Mixing*, pp. 245. Bamberg, 2003.
11. Linek, V., Moucha, T., and Sinkule, J., *Chem. Eng. Sci. 51*, 3203 (1996).
12. Kamieński, J., Aspects of Mechanically Agitated Gas—Liquid Systems, Monograph No. 147 (in Polish). Technical University of Cracow, 1993.
13. Kamieński, J. and Niżnik, J., *Inż. Chem. Proc. 20*, 299 (1999).
14. Kamieński, J. and Niżnik, J., *Inż. Chem. Proc. 22*, 591 (2001).
15. Orvalho, S. C. P., Vasconcelos, J. M. T., and Alves, S. S., *Proceedings of the 10th European Conference on Mixing*, pp. 461. Delft, 2000.
16. Karcz, J., Siciarz, R., and Bielka, I., *Preprints of the 11th European Conference on Mixing*, pp. 479. Bamberg, 2003.