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Experimental analysis of gas hold-up for gas-liquid system agitated in a vessel equipped with two impellers and vertical tubular baffles

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The influence of impellers system and type of liquid on the gas hold-up in the vessel has been presented in this paper. The analysis of gas hold-up was conducted on the basis of the data obtained in the vessel of the diameter D = 0.288 m, where the vessel was filled by a liquid up to the height H = 2D. The vessel was equipped in 24 vertical tubular baffles located on the circuit and two high-speed impellers situated on a shaft. Five different configurations of high-speed impellers were employed. The experiments in the gas-liquid system were conducted for setups which differed in capability of gas bubbles coalescence. The results of the experiment of the gas hold-up for the five impellers configurations and four gas-liquid systems were presented in the graphic form and they were described mathematically.

Keywords: gas-liquid system, vertical tubular baffles, system of two high-speed impellers.

INTRODUCTION

In the gas-liquid system it is important to know quantities such as: gas hold-up, volumetric mass transfer, size of gas bubbles, power consumption and residence time. These parameters are useful when designing reactors or bioreactors, where aeration of liquids or bio-liquids is demanded.

Research of gas hold-up in system agitated in a vessel equipped with two or more impellers were presented by John et al.[1], Bouaifi et al.[2], Majirova et al.[3], Moucha et al.[4], Pinelli et al.[5], Karcz et al.[6], Fujasova et al.[7], Shewale & Pandit[8], Bao et al.[9], Bao et al.[10], Cudak et al.[11]. An indicator of a volumetric factor of mass penetration in gas-liquid system in a vessel where more than one impeller used was a subject of research of John et al.[1], Moucha et al.[4], Pinelli et al.[5], Fujasova et al.[7], Shewale & Pandit[8], Cabaret et al.[12]. The power consumption for the gas-liquid system in a vessel with a few impellers situated on a shaft was characterised by Babalona et al.[13] using Newton's number, whereas Bouaifi & Roustan[14], Karcz et al.[6], Cudak et al.[11] described the power consumption as a ratio of P_g/P_o.

Bao et al.[9] and Bao et al.[10] described the total gas hold-up using equation

$$\varphi = \alpha P_m^{\beta} w_{og}^{\chi} \qquad (1)$$

where: φ – total gas hold-up,
P_m – mean total specific energy dissipation rate, W/kg
w_{og} – superficial gas velocity, m/s

and the equation where, additionally, the diameter of top impeller d_{top} and diameter of vessel D were taken into consideration:

$$\varphi = \alpha P_m^{\beta} w_{og}^{\chi} \left(\frac{d_{top}}{D}\right)^{\delta} \qquad (2)$$

Bouaifi et al.[2], Majirova et al.[3], Moucha el al.[4], Fujasova et al.[7], Xie et al.[15] used the following expression to describe the gas hold-up φ

$$\varphi = \alpha \left(\frac{P_g}{V}\right)^{\beta} w_{og}^{\chi} \qquad (3)$$

where: P_g – power consumption in aerated liquid, W
V – liquid volume, m^3.

The complex form of the equation (3), where glucose mass fraction x was included in the constant value α and in the exponents β, χ , was showed by Karcz et. al.[6].

In the vessel with single impeller, the gas hold-up with a usage of gas flow number $Kg = V_G/nd^3$ and Weber number $We = n^2d^3\varrho/\sigma$ was described with the equation

$$\varphi = aKg^{b}We^{c} f(Y) \qquad (4)$$

by Major-Godlewska et al.[16, 17].

The capability of gas bubbles to coalesce in distilled water and aqueous solutions of NaCl has been described by parameter Y defined by Machoň et al.[18]:

$$Y = 2 - exp\left(-\Psi^{+}\right) \qquad (5)$$

where $\Psi^{+} = \Psi/\Psi_{crit.}$. Variable Ψ has been defined by Lee & Meyrick[19] as follows

$$\Psi = \Delta\sigma \frac{RT}{2} = c\left(\frac{d\sigma}{dc}\right)^{2}\phi \qquad (6)$$

and φ has been defined

$$\phi = \left(\frac{1}{1+\dfrac{d\ln f}{d\ln c}}\right) \qquad (7)$$

where σ is the surface tension, R – the gas constant, T – the absolute temperature, c – the electrolyte concentration and f is the activity coefficient.

Cudak[20] proposed the equation

$$\varphi = aKg^{b}We^{c}(1+d\cdot x)^{e}M^{g} \qquad (8)$$

in order to describe the gas hold-up in the vessel with the single high-speed impeller. In Eq. (8) $M = g(\eta_L)^4(\varrho_L-\varrho_g)/\sigma^3(\varrho_L)^2$ denotes Morton number and x – mass fraction of sucrose.

Dispersion of gas in liquid is most often described in a vessel equipped in four standard flat baffles. The vessel equipped in vertical tubular baffles may be an alternative solution. Gas hold-up in the vessel with vertical tubular baffles, in which the liquid is stirred by one impeller was presented in the work of Major-Godlewska & Karcz[16, 17].

Vertical tubular baffles in the vessel are baffling similar to standard flat baffles. Moreover, vertical tubular baffles can be used as vertical coils, which enable heating, cooling or storing stable temperature of the process in the vessels of big volume. For example the heat transfer in liquids with the use of vertical coils was the subject of research of Havas et al.[21], Man et al.[22] and Karcz & Major[23, 24].

The influence of impellers system and the type of liquid on the gas hold-up in the vessel has been presented in the paper. The analysis of the gas hold-up has been conducted on the basis of data obtained in a vessel equipped with vertical tubular baffles and a system of impellers. The study has been conducted for the variable frequency of impellers rotations and variable intensity of gas flowrate.

EXPERIMENTAL

The measurements for gas-liquid system were conducted in a vessel of inner diameter $D = 0.288$ m. The vessel was filled by liquid up to the height $H = 0.576$ m. Vertical tubular baffles, consisted of $J = 24$ vertical tubes, were arranged symmetrically on the circuit of diameter $D_B = 0.7D$ inside the vessel. The outer diameter of a single tube was $B = 0.02D$. Gas was dispersed by means of the gas sparger which was formed in the shape of the ring with diameter $d_g = 0.7d$. The distance between vessel bottom and gas sparger was carried out $e = 0.5h_1$. Geometrical parameters of the vessel equipped with two impellers and vertical tubular baffles are shown in Figure 1. Five systems configuration high-speed impellers of diameter $d = 0.33D$ was used in the studies. Types of the impellers used in the study are illustrated in Figure 2. The configuration of the impellers used to the studies are shown in Table 1. The distance of the

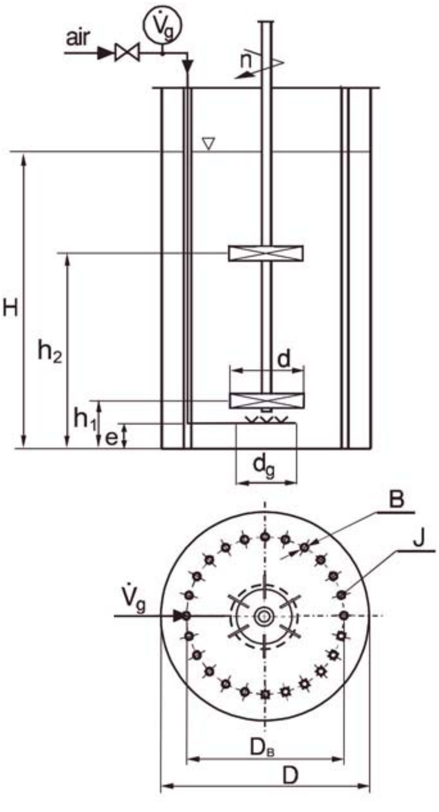

Figure 1. Geometrical parameters of the vessel

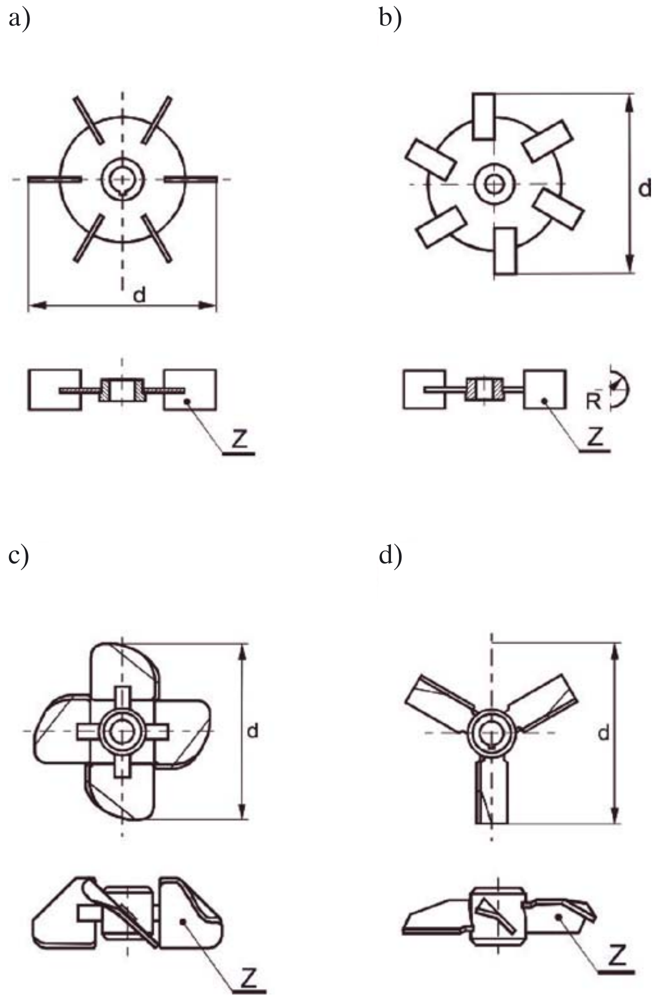

Figure 2. Types of the impellers: a) Rushton turbine (RT) d = 0.33D; Z = 6; b) Smith turbine (CD 6) d = 0.33D; Z = 6; c) A 315 d = 0.33D; Z = 4; d) HE 3 d = 0.33D; Z = 3

Table 1. The configuration of the impellers used to the studies

Configuration	Lower impellers	Upper impellers
1	Rushton turbine (RT)	Rushton turbine (RT)
2	Smith turbine (CD 6)	Rushton turbine (RT)
3	A 315	Rushton turbine (RT)
4	Rushton turbine (RT)	HE 3
5	Smith turbine (CD 6)	HE 3

impellers from the bottom of the vessel was $h_1 = 0.167H$ for the lower and $h_2 = 0.67H$ for the upper impeller.

The measurements have been conducted in the temperature of about 22ºC. The study in the gas-liquid system has been conducted for setups differing in capability of gas bubbles coalescence in liquid.

The gas used in the experiment was the air, and the liquid was distilled water, aqueous solutions of NaCl with two different concentrations ($c = 0.4$ kmol/m^3 and 0.8 kmol/m^3) and aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3% mass.

Just like in the papers of Major-Godlewskiej & Karcz[17] or Kiełbus-Rąpała & Karcz[25], the value of parameter Y is equal to 1 for system able to coalescence, air-distilled water. For the systems of lower ability to coalescence, such as the aqueous solutions NaCl of concentration $c = 0.4$ kmol/m^3 and $c = 0.8$ kmol/m^3, parameters Y have values 1.36 and 1.6, respectively.

Solution of carboxymethylocellulose (CMC) is classified as non-Newtonian, pseudoplastic fluid. Due to non-Newtonian character of the liquid in the case of aqueous solution of carboxymethylocellulose (CMC) rheological parameters of the liquid has been additionally experimentally measured. Rotational viscometer RT 10 HAAKE working in the system of two coaxial cylinders has been used to measure rheological properties. Rheological characteristics obtained $\tau = f(\gamma)$ enabled setting the value of flow index m and constant consistence k in Ostwald – de Waele model $\tau = k \cdot \gamma^m$ (Kembłowski[26]), which for the liquid used in the experiment in the temperature 22°C were adequately $m = 0.6847$, $k = 0.4118$ Ns^m/m^2.

The measurements were conducted for the range of good dispersion of gas bubbles in liquid for impellers speed n, 1/s ≤ 14.67 and the volumetric gas flow rate $\dot{V}_G$, $m^3/s \in < 1.11 \cdot 10^{-4}; 4.44 \cdot 10^{-4} >$.

The measurements of gas hold-up φ was calculated from equation

$$\varphi = \frac{V_G}{V_L + V_G} = \frac{H_G - H}{H_G} \tag{9}$$

where, the values H_G was determined as the mean of 10 values read from the scale located at the wall of the vessel for impeller speed n = const. and superficial gas velocity w_{og} = const., where $w_{og} = 4\dot{V}_G/\pi D^2$.

RESULTS AND DISCUSSION

The distribution of gas hold-up φ as the function of a number of gas flow Kg is presented in Figure 3. Comparing values φ obtained for three different gas-liquid systems (air- solution of CMC, air-distilled water and air-aqueous solution of NaCl of concentration $c = 0.8$ $kmol/m^3$) it is possible to state that the type of the liquid used is of great influence on the value φ. In the cases of analysis (Fig. 3) for the constant superficial gas velocity w_{og} higher gas hold-up φ for the gas-liquid system with lower ability to coalescence has been observed, which is for the air-aqueous solution of NaCl system. It has also been observed that the values φ decrease when the number of gas flow Kg increases, but for the system air-aqueous solution of CMC the drop of the value φ proportionally to the rise of the gas flow number is more gentle compared to the drop of value φ with the rising Kg number obtained in the system air-aqueous solution of NaCl $c = 0.8$ $kmol/m^3$.

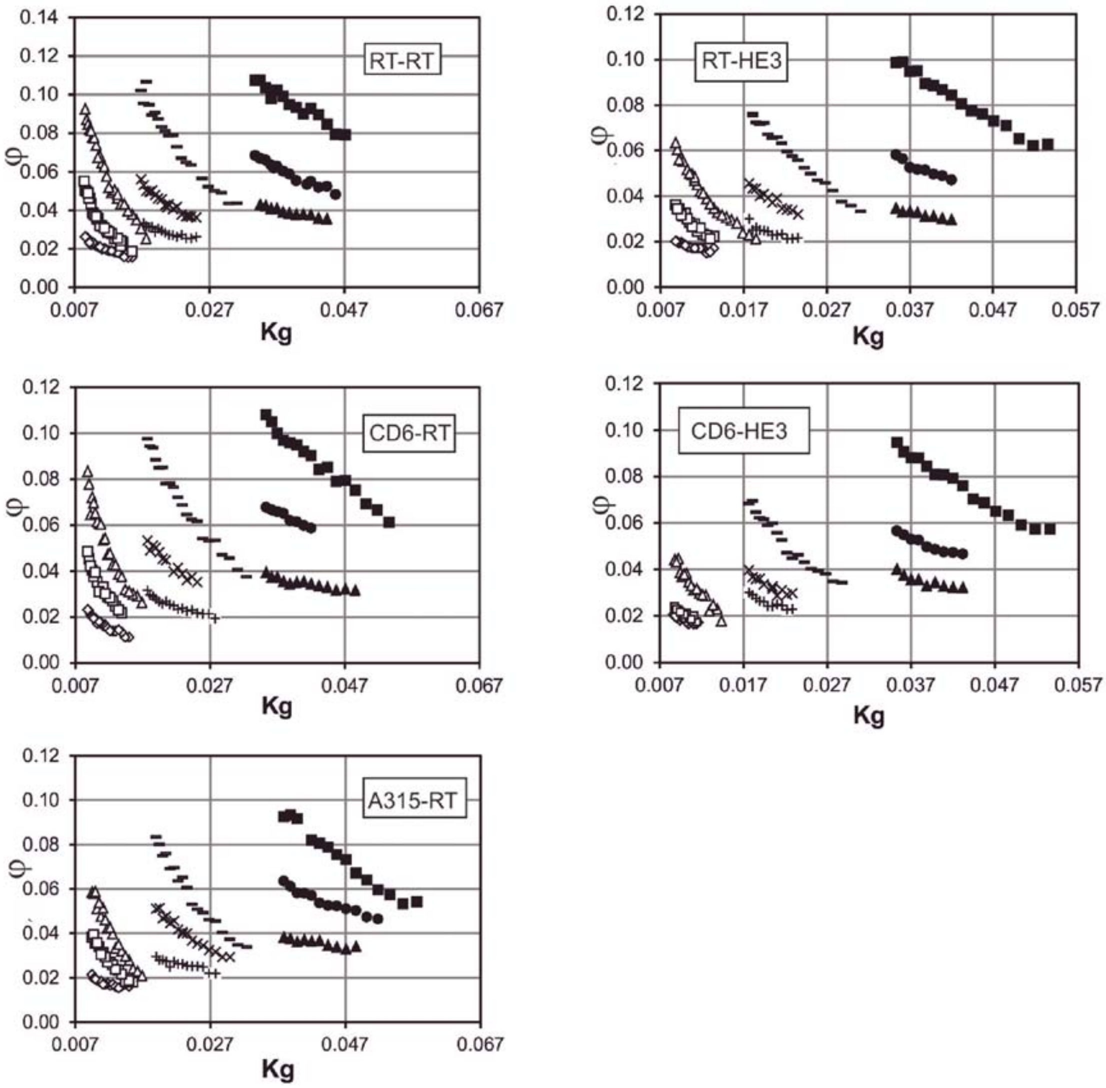

Figure 3. Dependence $\varphi = f(Kg)$ for the systems: ◊, +, ▲ – air-aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3%; □, x, ● – air-distilled water; Δ, –, ■ – air-aqueous solution of the NaCl with concentration c = 0.8 kmol/m³, where ◊, □, Δ: $w_{og} = 1.71 \cdot 10^{-3}$ m/s; +, x, -: wog = $3.41 \cdot 10^{-3}$ m/s; ▲, ●, ■: wog = $6.83 \cdot 10^{-3}$ m/s

The influence of the type of the lower impeller taking the Rushton turbine as the upper impeller on the gas hold-up φ in four liquids (aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3%, distilled water, aqueous solution of the NaCl with concentration $c = 0.4$ kmol/m^3 and $c = 0.8$ kmol/m^3) is presented in Figure 4. Analysing values φ for four gas-liquid systems and three different sets of impellers it has been stated that for constant superficial gas velocity w_{og} = const $= 6.83 \cdot 10^{-3}$ m/s the gas hold-up φ increases together with the increase of impeller speed n. For the system air-aqueous solution NaCl $c = 0.8$ kmol/m^3 the gas hold-up with $w_{og} = 6.83 \cdot 10^{-3}$ m/s with the increase of frequency of 1.34 1/s increases of about 7% for disc turbine impellers and for about 12% using the impeller A 315 in lower placement. Increasing superficial gas velocity from $w_{og} = 5.12 \cdot 10^{-3}$ m/s to $w_{og} = 6.83 \cdot 10^{-3}$ m/s with the constant impeller speed n = const = 12.33 1/s the gas hold-up φ increases about 10% if the lower impeller is one of the disc turbine impellers and about 5% if the lower impeller is the A 315 impeller and the liquid is aqueous solution NaCl $c = 0.8$ kmol/m^3. In the case when the data obtained for the air-distilled water is taken into analysis, then for the superficial gas velocity $w_{og} = 6.83 \cdot 10^{-3}$ m/s the impeller speed $n = 13.67$ 1/s and $n = 12.33$ 1/s the highest values φ has been obtained for the Smith turbine setup (lower impeller) – Rushton turbine (upper impeller). Such setup is less favourable for $w_{og} = 6.83 \cdot 10^{-3}$ m/s and $w_{og} = 5.12 \cdot 10^{-3}$ m/s and the impeller speed $n = 13.67$ 1/s and $n = 12.33$ 1/s, when the gas hold-up φ is aqueous solution of CMC. From the data analysis presented in Fig. 4 it turns out that for the system air-aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3% for $w_{og} = 6.83 \cdot 10^{-3}$ m/s and $w_{og} = 5.12 \cdot 10^{-3}$ m/s and $n = 13.67$ 1/s and n = 12.33 1/s using two Rushton impellers is more beneficial.

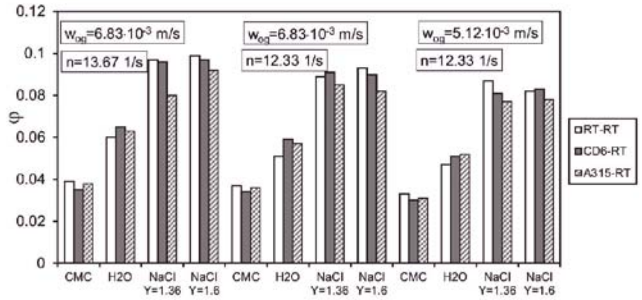

Figure 4. Dependence φ = f(type of liquid) for the systems: air-aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3 %; air-distilled water; air-aqueous solution of the NaCl with concentration c = 0.4 kmol/m^3 (where Y = 1.36) and c = 0.8 kmol/m^3 (where Y = 1.6); impellers lower – upper: Rushton turbine – Rushton turbine, Smith turbine – Rushton turbine, A315 – Rushton turbine

A similar analysis of gas hold-up φ has been conducted for the set of impellers, where HE 3 has been used as the upper impeller, and the Rushton turbine or Smith turbine as the lower impeller. Dependence φ = f (type of liquid) for four gas-liquid systems with the constant impeller speed $n = 12.33$ 1/s and two different superficial gas velocity $w_{og} = 1.71 \cdot 10^{-3}$ m/s and w_{og} = $6.83 \cdot 10^{-3}$ m/s has been presented in Fig. 5. Analysing

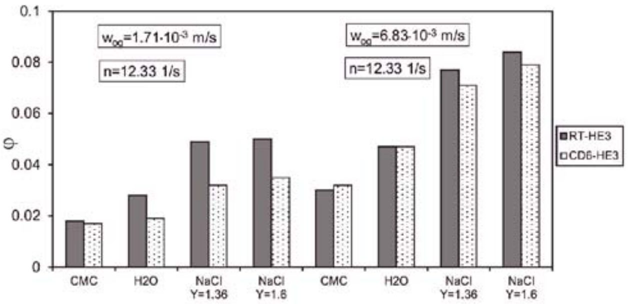

Figure 5. Dependence φ = f(type of liquid) for the systems: air-aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3%; air-distilled water; air-aqueous solution of the NaCl with concentration c = 0.4 kmol/m^3 (where Y = 1.36) and c = 0.8 kmol/m^3 (where Y = 1.6); impellers lower – upper: Rushton turbine – HE 3, Smith turbine – HE 3

data presented in Fig. 5 it is possible to state that in the majority of cases measured it is more favourable for the gas hold-up to use the setup Rushton turbine (lower impeller) – HE 3 (upper impeller).

The gas hold-up φ with the fixed lower impeller (Rushton turbine and Smith turbine) variable upper impeller (HE 3 and Rushton turbine) has been analysed on the basis of data presented in Figure 6. Weaker gas hold-up in liquid has been noticed when the impeller HE 3 is used in the system as the upper impeller.

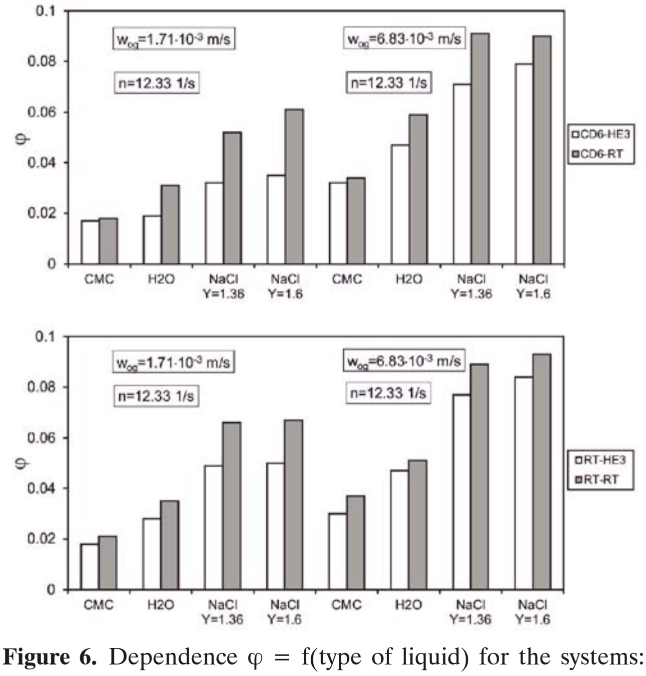

Figure 6. Dependence φ = f(type of liquid) for the systems: air-aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3%; air-distilled water; air-aqueous solution of the NaCl with concentration c = 0.4 kmol/m^3 (where Y = 1.36) and c = 0.8 kmol/m^3 (where Y = 1.6); impellers lower – upper: Smith turbine – HE 3, Smith turbine – Rushton turbine and Rushton turbine – HE 3, Rushton turbine – Rushton turbine

The results of measurement of the gas hold-up φ obtained for the impeller systems tested and for the setup air-aqueous solution CMC has been described mathematically in the equation

$$\varphi = A Kg^B We^C \tag{10}$$

where: Kg – number of gas flow; We – Weber number.

Values of coefficient *A* and exponents *B* and *C* of the equation (10) for the system air-aqueous solution CMC has been presented in Table 2. The equation (10) presents experimental data with the average relative error Δ not exceeding 5%.

The measurement results for the gas hold-up φ for the system air-distilled water and air-aqueous solutions NaCl (c = 0.4 kmol/m^3, c = 0.8 kmol/m^3) has been described in the equation:

$$\varphi = AKg^B We^C Y^D \tag{11}$$

where apart from the number of gas flow *Kg* and Weber number *We* parameter *Y* has been included describing abilities of the system to coalescence.

The values of coefficient *A* and exponents *B*, *C*, *D* of the equation (11) and the average relative error for the systems air-distilled water and air-aqueous solution NaCl have been presented in Table 3.

The results of the gas hold-up φ for the vessel with vertical tubular baffles and system of two impellers on the common shaft (A315 (lower) – Rushton turbine (upper)) were compared with values reported by Adamiak[27] (Fig. 7) obtained in the similar geometrical vessel with four planar baffles and the same system of impellers. The values of the gas hold-up φ for the system air-distilled water Adamiak[27] described using equation (10). In Eq. (10) the constant *A* and expolents *B* and *C* are equal to $A = 0.62 \cdot 10^{-4}$, $B = 0.58$, $C = 1.23$ for the system of the impellers A315 – Rushton turbine operating in the vessel with the four planar baffles[27]. The equation proposed by Adamiak[27] concerns higher gas flow number *Kg* in comparison to the values of the *Kg* presented in this work. It means, that when value φ is defined assuming w_{og} = const, higher values of impeller speed *n* of are used in the vessel with vertical tubular baffles compared to the geometrical system with planar baffles.

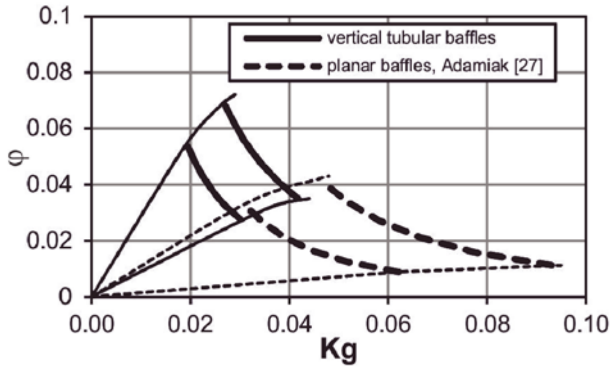

Figure 7. Dependence φ = f(Kg) for the systems: air-distilled water; impellers: A 315 (lower) – Rushton turbine (upper); baffles: vertical tubular and planar, superficial gas velocity: $w_{og} = 3.41 \cdot 10^{-3}$ m/s; $w_{og} = 5.12 \cdot 10^{-3}$ m/s

SUMMARY

On the basis of the measurements results for four gas-liquid systems, (where there were distilled water, aqueous solutions NaCl of two different concentrations 0.4 kmol/m^3 and 0.8 kmol/m^3, aqueous solution of carboxymethylocellulose (CMC) of concentration 2.3%) and five sets of impellers (RT – RT, CD 6 – RT, A 315 – RT, RT – HE 3, CD 6 – HE 3) it has been stated that the vessel equipped with vertical tubular baffles may be an alternative solution as a vessel with the impeller used to stir gas-liquid systems.

The content of gas in liquid in all cases tested increases when the impeller speed and gas flow rate increase. Gas hold-up φ in the liquid significantly depends on the physical properties of liquid. The weakest gas hold-up in liquid has been observed for the system air-aqueous solutions CMC. On the basis of the data obtained for the five analysed sets of impellers it is possible to state that each of them can be recommended to be used in gas-liquid systems. The choice of the set should be made depending on the liquid properties (Newtonian or non-Newtonian liquid).

SYMBOLS

B outer diameter of the vertical tubular baffles, m
c electrolyte concentration, kmol/m^3
D inner diameter of the vessel, m

Table 2. Values of coefficient A and exponents B, C in Eq. (10). Range of superficial gas velocity w_{og}, m/s∈<1.71 · 10^{-3}; 6.83 · 10^{-3}>

Impeller		A	B	C	Range	
lower	upper					
RT	RT	$1.41 \cdot 10^{-3}$	0.389	0.597	Kg∈<0.86 · 10^{-2}; 4.44 · 10^{-2}>	We∈<835; 2700>
CD 6	RT	$9.67 \cdot 10^{-4}$	0.461	0.671	Kg∈<0.88 · 10^{-2}; 4.86 · 10^{-2}>	We∈<890; 2555>
A 315	RT	$3.96 \cdot 10^{-3}$	0.477	0.499	Kg∈<0.95 · 10^{-2}; 4.86 · 10^{-2}>	We∈<880; 2210>
RT	HE 3	$1.29 \cdot 10^{-3}$	0.367	0.575	Kg∈<0.88 · 10^{-2}; 4.2 · 10^{-2}>	We∈<1105; 2545>
CD 6	HE 3	$7.12 \cdot 10^{-4}$	0.424	0.688	Kg∈<0.88 · 10^{-2}; 4.32 · 10^{-2}>	We∈<1520;2545>

Table 3. Values of coefficient A and exponents B, C, D in Eq. (11). Range of superficial gas velocity w_{og}, m/s ∈<1.71 · 10^{-3}; 6.83 · 10^{-3}>

Impeller		A	B	C	D	±Δ, %	Range
lower	upper						
RT	RT	$3.59 \cdot 10^{-4}$	0.225	0.77	1.097	10.4	Kg∈<0.85 · 10^{-2}; 4.71 · 10^{-2}> We∈<640; 2825>
CD 6	RT	$3.29 \cdot 10^{-4}$	0.318	0.825	1.013	7.3	Kg∈<0.88 · 10^{-2}; 5.36 · 10^{-2}> We∈<640; 2575>
A 315	RT	$1.6 \cdot 10^{-4}$	0.313	0.919	0.87	8.2	Kg∈<0.95 · 10^{-2}; 5.76 · 10^{-2}> We∈<700; 2490>
RT	HE 3	$4.33 \cdot 10^{-4}$	0.349	0.781	1.087	7.5	Kg∈<0.88 · 10^{-2}; 5.36 · 10^{-2}> We∈<580; 2575>
CD 6	HE 3	$3.1 \cdot 10^{-4}$	0.536	0.903	1.026	9.0	Kg∈<0.88 · 10^{-2}; 5.36 · 10^{-2}> We∈<960; 2570>

D_B diameter of the vertical tubular baffles, m
d diameter of the impeller, m
d_g diameter of the gas sparger, m
d_{top} diameter of top impeller, m
e distance between gas sparger and the bottom of the vessel, m
f activity
H liquid height in the vessel, m
H_G height of the gas-liquid system in the vessel, m
h_1, h_2 distance between impeller and the bottom of the vessel, m
J number of tubular baffles
k consistency index, Pas^m
m flow index
n impeller speed, 1/s
P_g power consumption for gas-liquid system, W
P_m mean total specific energy dissipation rate, W/kg
P_o power consumption for liquid phase, W
R gas constant, J/molK
T absolute temperature, K
V_G gas volume in the liquid, m^3
V_L liquid volume in the vessel, m^3
$\dot{V}_G$ the volumetric gas flow rate, m^3/s
w_{og} superficial gas velocity, m/s
Y parameter defined by Eq. (5)
Z number of impeller blades

Greek symbols

Ψ parameter defined by Eq. (6)
γ shear rate, 1/s
η dynamic viscosity, Pas
φ gas hold-up defined by Eq. (9)
ϱ liquid density, kg/m^3
σ surface tension, $N\ m^{-1}$
τ shear stress, Pa

LITERATURE CITED

1. John, A.H., Bujalski, W. & Nienow, A.W. (1997). A novel reactor with independently-driven dual impellers for gas-liquid processing. *Recents Progr. Genie Proced.* 11, 5, 169–176.

2. Bouaifi, M., Hebrard, G., Bastoul, D. & Roustan, M. (2001). A comparative study of gas hold-up, bubble size, interfacial area and mass transfer coefficients in stirred gas-liquid reactors and bubble columns. *Chem. Eng. Proc*., 40, 97–111. DOI: 10.1016/S0255-2701(00)00129-X.

3. Majirova, H., Pinelli, D., Machon, Y. & Magelli, F. (2003). Gas flow behavior in a two-phase sparged reactor stirred with multiple turbines. 11th European Conference on Mixing, 14–17 October 2003 (pp. 245–252), Bamberg.

4. Moucha, T., Linek, V. & Prokopova, E. (2003). Gas hold-up, mixing time and gas-liquid volumetric mass transfer coefficient of various multiple-impeller configurations: Rushton turbine, pitched blade and techmix impeller and their combinations. *Chem. Eng. Sci*., 58, 1839–1846. DOI: 10.1016/S0009-2509(02)00682-6.

5. Pinelli, D., Bakker, A., Myers, K.J., Reeder, M.F., Fasano, J. & Magelli, F. (2003). Some features of a novel gas dispersion impeller in a dual-impeller configuration. *Trans IChemE*, 81, 448–454.

6. Karcz, J., Siciarz, R. & Bielka, I. (2004). Gas hold-up in a reactor with dual system of impellers. *Chem. Pap*., 58(6), 404–409.

7. Fujasova, M., Linek, V., Moucha, T. & Prokopova, E. (2004). Energy demands of different types in gas-liquid dispersions. *Sep. Purif. Technol.* 39, 123–131. DOI: 10.1016/j.seppur.2003.12.015.

8. Shewale, S.D. & Pandit, A.B. (2006). Studies in multiple impeller agitated gas-liquid contactors. *Chem. Eng. Sci*., 61, 489–504. DOI: 10.1016/j.ces.2005.04.078.

9. Bao, Y., Yang, J., Chen, L. & Gao, Z. (2012). Influence of the top impeller diameter on the gas dispersion in a sparged multi-impeller stirred tank. *Ind. Eng. Chem. Res*., 51, 12411––12420. DOI: 10.1021/ie301150b.

10. Bao, Y., Wang, B., Lin, M., Gao, Z. & Yang, J. (2015). Influence of impeller diameter on overall gas dispersion properties in a sparged multi-impeller stirred tank. *Chin. J. Chem. Engineer.* 23, 890–896. DOI: 10.1016/j.cjche.2014.11.030.

11. Cudak, M., Kiełbus-Rąpała, A., Major-Godlewska, M. & Karcz, J. (2016). Influence of different factors on momentum transfer in mechanically agitated multiphase systems. *Chem. Process. Eng.* 37(1), 41–53. DOI: 10.1515/cpe-2016-0005.

12. Cabaret, F., Fradette, L. & Tanguy, P.A. (2008). Gas-liquid mass transfer in unbaffled dual-impeller mixers. *Chem. Eng. Sci*., 63, 1636–1647. DOI: 10.1016/j.ces.2007.11.028.

13. Babalona, E., Bahouma, D., Tagia, S., Pantouflas, E. & Markopoulos, J. (2005). Power consumption in dual impeller gas-liquid contactors: impeller spacing, gas flow rate, and viscosity effects. *Chem. Eng. Technol.* 28(7), 802–806. DOI: 10.1002/ceat.200407160.

14. Bouaifi, M. & Rouston, M. (2001). Power consumption, mixing time and homogenisation energy in dual-impeller agitated gas-liquid reactors. *Chem. Eng. Process*. 40, 87–95. DOI: 10.1016/S0255-2701(00)00128-8.

15. Xie M., Xia J., Zhou Z., Chu J., Zhuang Y. & Zhang S. (2014). Flow pattern, mixing, gas hold-up and mass transfer coefficient of triple-impeller configurations in stirred tank bioreactors. *Ind. Eng. Chem. Res*., 53, 5941–5953.

16. Major-Godlewska, M. & Karcz, J. (2003). Gas hold-up and power consumption for gas-liquid system agitated in a stirred tank equipped with vertical coil. *Chem. Pap*., 57(6) 432–437.

17. Major-Godlewska, M. & Karcz, J. (2011). Process characteristics for a gas-liquid system agitated in a vessel equipped with a turbine impeller and tubular baffles. *Chem. Pap*., 65(2), 132–138. DOI: 10.2478/s11696-010-0080-0.

18. Machoň, V., Vlček, J. & Kudrna, V. (1978). *Gas hold-up in agitated aqueous solutions of strong inorganic salts.* Coll. Czech. Chem. Commun. 43, 593–603. dx.doi.org/10.1135/cccc19780593.

19. Lee, J.C. & Meyrick, D.L. (1970). Gas-liquid interfacial areas in salt solutions in an agitated tank. *Trans. Inst. Chem. Eng.* 48, 37–45.

20. Cudak, M. (2014). Hydrodynamic characteristics of mechanically agitated air-aqueous sucrose solutions., *Chem. Process. Eng.* 35(1), 97–107. DOI: 10.2478/cpe-2014-0007.

21. Havas, G., Deak, A. & Sawinsky, J. (1982). Heat transfer coefficients in an agitated vessels using vertical tube baffles. *Chem. Eng. J*. 28, 161–165.

22. Man, K.L., Hughes, W. & Moody, G.W. (1991). The effect of rheology and baffle design on the power and heat transfer performance in stirred vessels using vertical tubular baffles. *7th European Congress on Mixing*, 18–20 september 1991 (pp. 321–332). Brugge, Belgium.

23. Karcz, J. & Major, M. (2001). Experimental studies of heat transfer in an agitated vessel equipped with vertical tubular coil. *Inż. Chem. Proc.* 22, 445–459.

24. Karcz, J. & Major, M. (2001). Badania wymiany ciepła w mieszalniku z wężownicą pionową. *Inż. Chem. i Proc*., 22, 3C, 639–644.

25. Kiełbus-Rąpała, A. & Karcz, J. (2012). Experimental analysis of the hydrodynamics of a three-phase system in a vessel with two impellers. *Chem. Pap*., 66(6), 574–582. DOI: 10.2478/s11696-012-0157-z.

26. Kembłowski, Z. (1973). *Reometria płynów nieniutonowskich*, WNT, Warszawa.

27. Adamiak, R. (2005*). Experimental studies of conditions for gas dispersion in liquid in the stirred tank on different scale*. PhD Thesis, Politechnika Szczecińska, Szczecin (in Polish).