An Efficiency of the Liquid Homogenization in Agitated Vessels Equipped with Off-Centred Impeller*

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Received 1 April 2005

Efficiency of the liquid homogenization in agitated vessels (with inner diameter D) equipped with off-centred impeller is analyzed. Experimental studies of the mixing time were carried out in a 0.270 m^3 vessel using unsteady-state thermal method. Eccentrically located propeller and pitched blade turbines were used for agitation of Newtonian liquid (aqueous solution of molasses) within the turbulent regime of the fluid flow.

Assuming constant value of the specific mixing energy, ε, similar values of the mixing times, t_{m}, were observed for propeller and pitched blade turbine with three blades. Mixing time was positively influenced by the increase of impeller diameter and the number of impeller blades.

Assuming constant value of specific energy, ε, the lowest dimensionless mixing time, Θ, corresponded to the eccentric pitched three-blade turbine with diameter $d = 0.5\ D$. Taking into account different criteria proposed in literature, eccentric propeller ($e/R = 0.57$) can be recommended for liquid homogenization with the most efficiency in the unbaffled agitated vessel, within the range of the performed measurements.

Mixing time is a very important parameter [1—4], which is used to estimate efficiency of the liquid homogenization in an agitated vessel. *Zlokarnik* [5] compared different impellers used for agitation of the liquid within the turbulent regime of the fluid flow on the basis of the following homogenization criterion

$$\frac{PD\rho^2}{\eta^3} = f\left(\frac{t_{\mathrm{m}}\eta}{D^2\rho}\right) \qquad (1)$$

which correlates modified power number $PD\rho^2/\eta^3$ with the modified mixing number $t_{\mathrm{m}}\eta/D^2\rho$. Symbols used in eqn (*1*) describe the following variables: t_{m} – mixing time, P – power consumption, D – inner diameter of the agitated vessel, ρ – liquid density, η – liquid viscosity. Based on the criterion (*1*), it is to be estimated which type of the agitator realizes for a given liquid and the vessel of diameter D the required mixing time t_{m} with the lowest power consumption P and, therefore, the minimum mixing energy (Pt_{m} = const).

Studies of the energy required for liquid homogenization in both baffled and unbaffled agitated vessels were conducted by *Novak* and *Rieger* [6]. They proposed the following dimensionless criterion E_{t} to compare the effects of the mixing in both vessels

$$E_{\mathrm{t}} = \frac{E_{\mathrm{m}}t_{\mathrm{m}}^2}{\rho D^5} = Ne\,(nt_{\mathrm{m}})^3\left(\frac{d}{D}\right)^5 = Ne\Theta^3\left(\frac{d}{D}\right)^5 \qquad (2)$$

where mixing energy

$$E_{\mathrm{m}} = Pt_{\mathrm{m}} \qquad (3)$$

and $\Theta = nt_{\mathrm{m}}$ is the dimensionless mixing time (where n is the agitator speed), $Ne = P/n^3d^5\rho$ power number, d/D ratio of impeller diameter d to agitated vessel diameter D. The criterion E_{t} corresponds to dimensionless mixing energy. Rearranging this criterion, equivalent relationship can be obtained between power number Ne, dimensionless mixing time Θ and geometrical simplex d/D. The agitators should be recommended, for which lower value of the E_{t} is ascribed because it corresponds to the higher mixing efficiency. Out of two compared agitators, better will be an agitator for which lower power consumption P is required to obtain a given mixing time t_{m} of the liquid in an agitated vessel of a given geometry.

The results obtained in the fully turbulent region of the liquid flow [6] show that the impellers operating in unbaffled vessels require smaller energy than the impellers to get the same level of homogenization in the

*Presented at the 32nd International Conference of the Slovak Society of Chemical Engineering, Tatranské Matliare, 23—27 May 2005.

agitated vessels equipped with four standard baffles. *Fort et al.* [7] studied the efficiency of the blending in the baffled agitated vessel equipped with the pitched blade turbine with three blades, differing in the vessel to impeller diameter ratios, D/d. The authors assumed the criterion (*2*) to estimate the blending efficiency. Based on the experimental data analysis, it was found that higher blending efficiency is reached for lower value of the criterion E_t. The value of the criterion (*2*) decreases with the decrease of the pitch of the impeller blade. Moreover, the criterion E_t decreases with the decrease of the vessel/impeller diameter ratio.

Results of the studies concerning efficiency of the liquid homogenization in fully baffled vessel with a centrally located impeller are presented in papers [8—11]. In order to estimate the influence of the energy required for liquid homogenization, *Shaw* [8] conducted three series of measurements in an agitated vessel with four baffles. In the first series, eight impellers, which worked at the same level of the specific mixing energy ($\varepsilon_\mathrm{V} = 4$ W m^{-3}), were tested. The second series was conducted with three impellers only, which operated at the specific energy levels equal to half and double of that used in the first series. The last series was carried out for one impeller with different diameters supplied with identical specific mixing energy as in the first series. The tests revealed that the mixing time was independent of the impeller type, assuming that all impellers were working at the same level of the specific energy. Moreover, for given specific energy the mixing time is inversely proportional to the 1.5 power of the impeller to vessel diameter ratio, d/D, and to the cube root of the power consumption. *Herbert et al.* [9] proposed the following equation to calculate dimensionless mixing time Θ in the baffled agitated vessel with a centrally located impeller

$$\Theta = 6.7 \left(\frac{d}{D}\right)^{-\frac{5}{3}} Ne^{-\frac{1}{3}} \qquad (4)$$

Measurements of the mixing time [9] were conducted for five types of impellers. Comparable mixing times were obtained for different impellers operating at the same level of power consumption. *Ruszkowski* [10] studied liquid homogenization using eight types of impellers in an agitated vessel with baffles. The author proved that the impeller type has no influence on the mixing time. *Ruszkowski* [10] compiled the results of the measurements for the centrally located impellers with different diameters d and number of blades Z by means of the following equation

$$t_\mathrm{m} = 5.91\, D^{\frac{2}{3}} \left(\frac{P}{V_\mathrm{L}\rho}\right)^{-\frac{1}{3}} \left(\frac{D}{d}\right)^{\frac{1}{3}} \qquad (5)$$

The results of the mixing time studies conducted in a baffled agitated vessel [10] show that the power requirement is an important factor influencing the mixing time.

Unbaffled agitated vessels with eccentrically located shaft of the impeller are commonly used in food and chemical industries, especially in the case when the presence of baffles affects volume of dead zones of the agitated liquid. Eccentric position of the impeller shaft improves the liquid mixing compared to homogenization realized in an unbaffled vessel equipped with centrally located impeller. The effect of the shaft eccentricity on the power consumption P was studied experimentally [12—14]. The results of these studies revealed that the power consumption increases with the increase of the impeller eccentricity, e/R. Moreover, within the turbulent regime of the liquid flow, the values of the power number Ne are similar for both baffled agitated vessel with centred impeller and unbaffled one equipped with the off-centred impeller, located in the most eccentric position.

Recently, mixing of liquids in unbaffled vessels was intensively studied [13, 15—20]. *Seichter et al.* [18] investigated the mixing time in an unbaffled vessel equipped with eccentrically located axial impeller. *Karcz et al.* [20, 21], *Cudak* [14], and *Szoplik* [22] discussed distribution of the heat-transfer coefficient and the friction coefficient in the region of the wall of the jacketed vessel, as well as the mixing time. Deformation of the axial and angular profiles of the shear rate, friction coefficient and heat-transfer coefficient was observed with the increase of the eccentricity e/R of the impeller shaft [14, 20]. *Karcz* and *Cudak* [13] experimentally studied efficiency of the heat-transfer process in a jacketed agitated vessel equipped with off-centred propeller and HE 3 impeller. The influence of the eccentrically located up- or down-pumping propeller on the mixing time was analyzed by *Karcz* and *Szoplik* [19—22]. The investigations carried out in an unbaffled vessel with eccentrically located propeller agitator [22] show that the mixing time decreases with the increase of the impeller eccentricity e/R, whereas the power consumption P increases.

In this study, an effect of the impeller type on the mixing time and efficiency of the liquid homogenization in the agitated vessel equipped with off-centred impeller has been analyzed. Mixing time t_m as a function of the specific mixing energy ε has been compared for a centric and eccentric position of the propeller and pitched blade turbine. Dimensionless mixing time Θ has been related with the modified Reynolds number $Re_\mathrm{P,V}$. Mixing energy $E_\mathrm{m} = Pt_\mathrm{m}$, dimensionless criterion $E_\mathrm{t} = E_\mathrm{m}t_\mathrm{m}^2/\rho D^5$, and dimensionless mixing number $t_\mathrm{m}\eta/D^2\rho$ have been assumed as the efficiency criteria to estimate effectiveness of the liquid homogenization.

EXPERIMENTAL

Measurements of the mixing time were carried out in an agitated vessel with the liquid volume $V_\mathrm{L} = 0.27$ m^3, using unsteady-state thermal method. Unbaffled

Table 1. Geometry of Agitated Vessel and Impellers Used

Agitated vessel		Agitator	Z	d/m	S/d*
D/m	0.7	Propeller (P)	3	0.33 D	1
H/m	D	Pitched blade turbine (PBT-3)	3	0.33 D	45°
h/m	0.33 H	Pitched blade turbine (PBT)	3	0.5 D	45°
e/R	0, 0.43, 0.57	Pitched blade turbine (PBT-6)	6	0.33 D	45°

*Pitch of the propeller blade, β, in the case of pitched blade turbines.

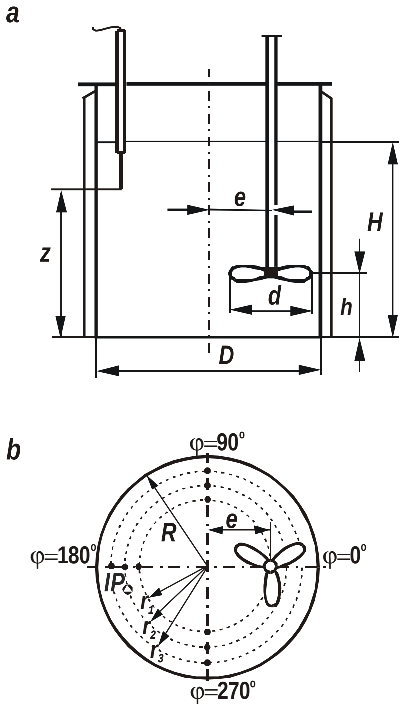

Fig. 1. a) Geometrical parameters of the agitated vessel; b) coordinates r, φ of the measuring points during measurements of the mixing time, t_{m}.

vessel with inner diameter $D = 0.7$ m was filled with Newtonian liquid up to a height of $H = 0.7$ m (Fig. 1a). Propeller or pitched blade turbine of diameter $d = 0.33$ D or 0.5 D was mounted on the eccentrically located shaft ($e/R = 0.57$ for $d/D = 0.33$ or $e/R = 0.43$ for $d/D = 0.5$). The distance h between impellers and flat bottom of the vessel, *i.e.* off-bottom clearance was equal to 0.33 H. Measurements of the mixing time for centric position ($e/R = 0$) of the impellers were also carried out for comparative purposes. Geometric details of the vessel (Fig. 1a) and impellers used are collected in Table 1.

Aqueous solution of molasses with the viscosity of 4.5 mPa s at a temperature of 20 ℃ was mixed within the turbulent regime of the liquid flow in the agitated vessel, $Re \in (1 \times 10^4;\ 8 \times 10^4)$.

Experiments were carried out by means of the computer-aided unsteady-state thermal method. Pulse injection of the tracer dosage was made onto the liquid surface at the same position IP ($r/R = 0.71$, $\varphi = 200°$) for all the measurements. After injection of a given amount of tracer V_{a} ($V_{\mathrm{a}} = 0.0026\ V_{\mathrm{L}}$), temperature changes were registered using digital temperature probe located at the positions described by the coordinates (r, φ, and $z = 0.71\ H$). The pulse response was measured at different points identified by means of radial (r_1, r_2, r_3) and angular ($\varphi = 0°$, 90°, 180°, and 270°) coordinates (Fig. 1b). As the mixing time, t_{m}, the time required for 95 % liquid homogenization was assumed. Detailed description of the experimental set-up and thermal method for the mixing time estimation was given elsewhere [19—22].

RESULTS AND DISCUSSION

The results of experiments show that the mixing time, t_{m}, obtained for a given value of the Reynolds number (Re = const) depends on the position of the measuring probe within the vessel and on the type of the eccentrically located agitator. The examples of the relationships $t_{\mathrm{m}} = f(r, \varphi)$ for up-pumping propeller and pitched blade turbines differing in diameter d of the impeller and number Z of impeller blades are presented in Fig. 2 for assumed value of Re = 32000. The longest mixing time was observed for propeller (Fig. 2a). Substitution of propeller by means of pitched blade turbine with three blades caused the decrease of the mixing time (Figs. 2a, b). The value of t_{m} decreased with the increase of the number of blades, Z, of the pitched blade turbine (Figs. 2b, c). Increase of the diameter d of the pitched blade turbine caused further, however, slighter decrease of the mixing time (Figs. 2b, d). As the experimental results presented in paper [19] showed, the mixing time does not depend on the position of the measuring point at the radial plane (r, φ) in an unbaffled agitated vessel equipped with a centrally located impeller. However, eccentric position of the impeller affects the distortion of the axially symmetrical flow of the liquid in the vessel. Motion of the liquid is more intensive in the part of the vessel, where the impeller is located closer to the vessel wall. Therefore, the mixing time is shorter in this region in comparison with the values of the t_{m} obtained for the other part of the agitated vessel. For this reason, the largest value of the t_{m} measured in the plane (r, φ) for a given impeller speed n, parameter e/R, and type of the agitator was assumed as the mixing time for further calculations

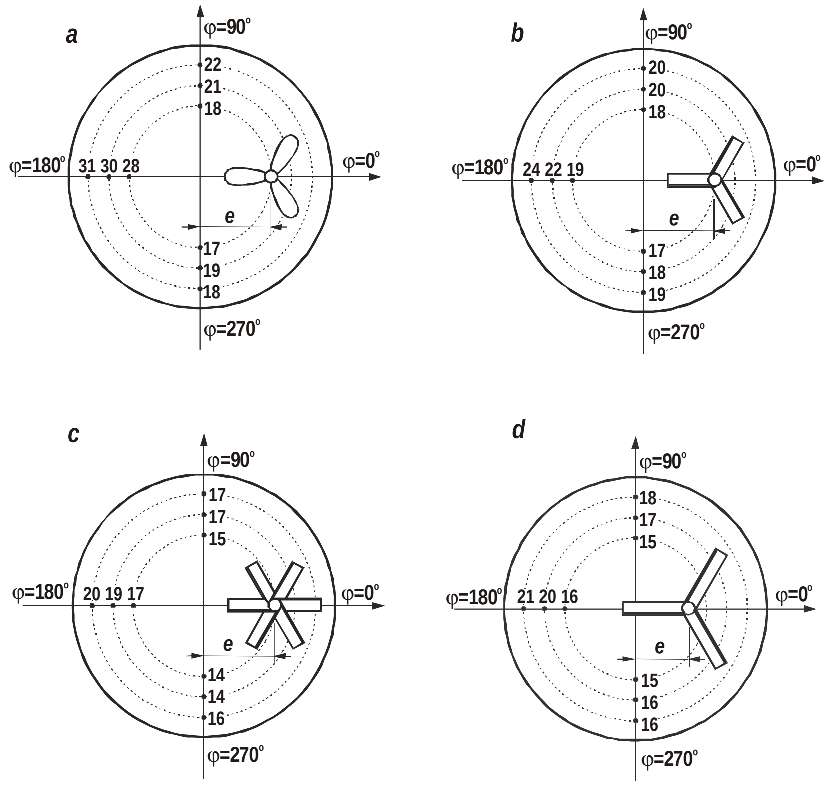

Fig. 2. The values of mixing time at individual measuring points within the agitated vessel at $Re = 3.2 \times 10^4$: *a*) eccentric ($e/R = 0.57$) propeller, P; *b*) PBT-3; *c*) PBT-6; and *d*) PBT ($e/R = 0.43$).

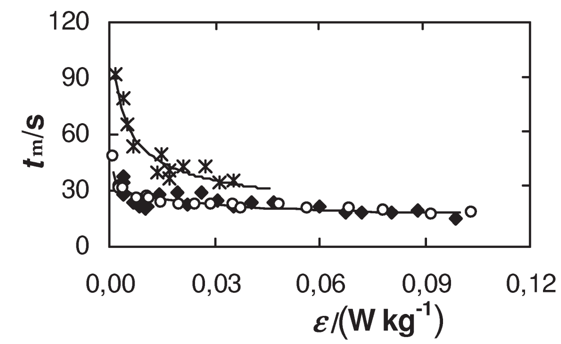

Fig. 3. Variation of the mixing time with specific mixing energy for centric ($e/R = 0$ (∗)) and eccentric ($e/R = 0.43$ (♦) or $e/R = 0.57$ (○)) position of the propeller; $d/D = 0.33$.

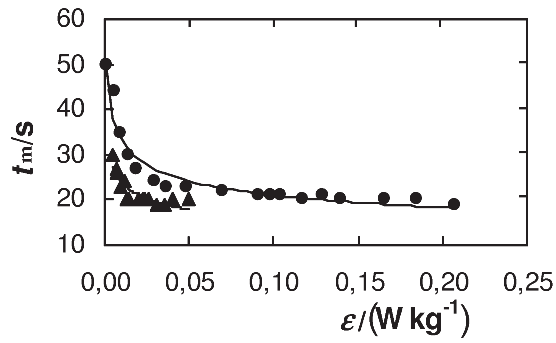

Fig. 4. The dependence $t_m = f(\varepsilon)$ for eccentrically located pitched blade turbine; $e/R = 0.57$; $d/D = 0.33$; PBT-3 (●); PBT-6 (▲).

concerning the agitated vessel with off-centred impeller.

Variation of the mixing time with specific energy, ε, for propeller and pitched blade turbines is compared in Figs. 3 and 4, respectively. Fig. 3 shows that the mixing time obtained for centrally positioned propeller is larger than that found for the same impeller in an eccentric location, especially within the low range of specific energy. Assuming constant value of the specific energy, ε, the lowest value of the mixing time corresponds to the eccentric pitched blade turbine with six blades (Fig. 4).

Power consumption required to reach given turbulence of the liquid differs for tested impellers. Within the turbulent regime, power number *Ne* is independent of the *Re* number, but it is a function of geometrical parameters of the agitator. The values of power numbers obtained by *Cudak* [14] for eccentric propeller and pitched blade turbines have been used for further analysis of the mixing time data. The results were compared assuming constant value of the specific energy ε equal to 0.03 W kg^{-1} (see Table 2). Taking into account the data for eccentric pitched three-blade turbine with diameter $d = 0.33\ D$ or $0.5\ D$ (lines 1 and 2 in Table 2), similar values of the mixing time t_m, but very different values of the dimensionless mixing time Θ, could be observed. The value of Θ for small impeller is about 2.35 times higher than that for the

Table 2. Comparison of the Mixing Time and Mixing Energy for Different Impellers; $\varepsilon = 0.03$ W kg^{-1}

Impeller type	Z	d/D	e/R	Ne	t_m/s	Θ	Re	$Re_{P,V} \times 10^{-13}$	E_m/J	E_t
PBT-3	3	0.33	0.57	1.0	24	54	30739	11.1	214	643
PBT	3	0.5	0.43	1.15	20	23	36039	13.7	201	415
PBT-3	3	0.33	0.57	1.0	24	54	30739	11.1	214	643
PBT-6	6	0.33	0.57	1.46	19	41	27668	9.4	179	336
P	3	0.33	0.57	0.28	23	79	63549	25.9	197	543
PBT-3	3	0.33	0.57	1.0	24	54	30739	11.1	214	643
P	3	0.33	0	0.21	34	132	64679	25.8	390	2349
P	3	0.33	0.57	0.28	23	79	63549	25.9	197	543

large pitched blade turbine. Simultaneously, Re number for small impeller is slightly lower and criterion E_t is by about 50 % higher comparing with a large impeller. However, mixing energy $E_m = Pt_m$ has very similar value in both cases. The values $t_m = 24$ s for PBT-3 and $t_m = 20$ s for PBT (lines 1 and 2 in Table 2) are not identical. The difference between them is equal to about 20 %. Taking it into account in the numerator of the definition (*2*), the value of the criterion E_t for PBT-3 impeller, higher about 44 %, is obtained.

Analogous comparison of results obtained for eccentric pitched blade turbine with diameter $d = 0.33$ D differing in number of the blades Z ($Z = 3$ or 6, lines 3 and 4 in Table 2) shows that dimensionless mixing time, Re number, mixing energy E_m, and the value of the criterion E_t are higher for the impeller with three blades.

The same values of mixing time were obtained when compared the data obtained for both eccentric impellers, propeller and pitched three-blade turbine (lines 5 and 6 in Table 2). Dimensionless mixing time Θ for both these agitators differs by about 46 % (higher value corresponds to the propeller). Power number, Ne, calculated for propeller is about three times lower than that obtained for pitched blade turbine. Moreover, computed Re and modified $Re_{P,V}$ numbers are approximately two times higher for propeller compared to pitched blade turbine.

Eccentric position of the agitator affects the decreasing of the mixing time. In this case tangential motion of the liquid in the unbaffled agitated vessel is reduced. The data for a centric and eccentric propeller are compared at lines 7 and 8 in Table 2. The values of the mixing time, t_m, and dimensionless time, Θ, obtained for an eccentric propeller ($e/R = 0.57$) are lower by about 48 % and 67 %, respectively, than those determined for a centric propeller ($e/R = 0$). Although power number Ne for the eccentric propeller is higher, mixing energy, E_m, and dimensionless criterion, E_t, are lower because mixing time, t_m, is shorter in this case. Taking into account this fact, unbaffled agitated vessels equipped with the eccentric propeller can be recommended for liquid homogenization, instead of the unbaffled vessels with a centric propeller.

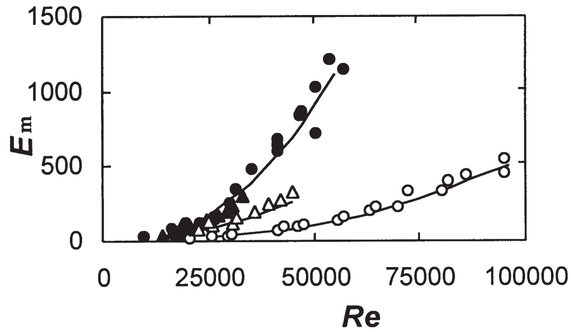

Fig. 5. Comparison of the dependence $E_m = f(Re)$ for different eccentric impellers used in the studies. P (○), PBT-3 (●), PBT-6 (▲) ($e/R = 0.57$). PBT (△) ($e/R = 0.43$, $d/D = 0.5$).

In this case, the values of E_m and E_t are only equal to 50 % and 23 %, respectively, of those values obtained for the agitated vessel with centric propeller.

Mixing energy as a function of Re number is compared for different types of eccentric impellers in Fig. 5. The lowest mixing energy is characteristic of propeller agitator, whereas the highest values of E_m correspond to the pitched blade turbine of diameter $d = 0.33$ D with three blades.

Taking into account the requirement of the power consumption for agitation, P, modified Reynolds criterion, $Re_{P,V}$, can be defined ($Re_{P,V} = [(P/V)D^4\rho^2]/\eta^3$). Correlating the results in the form of the dependence $\Theta = f(Re_{P,V})$, eccentric impellers have been compared more precisely. According to the data presented in Fig. 6 the lowest dimensionless mixing time is ascribed to the eccentric pitched blade turbine of diameter $d = 0.5$ D with three blades. The highest values of Θ are characteristic of propeller and pitched three-blade turbine with diameter $d = 0.33$ D.

Experimental results for eccentric impellers were correlated also using the relationship $E_t = f(Re)$ as shown in Fig. 7, where E_t is the dimensionless criterion proposed by *Novak* and *Rieger* [6]. Based on these data, the relations between different types of impellers are analogous to that shown in Fig. 5 ($E_m = f(Re)$). It is worth to notice that criterion E_t (eqn (*2*)) is not a function of the liquid viscosity η. In the relationship

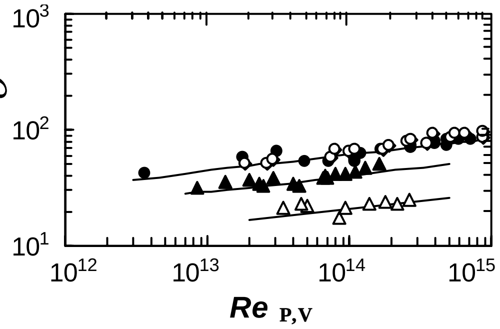

Fig. 6. Comparison of the dependence $\Theta = f(Re_{\mathrm{P,V}})$ for different eccentric impellers used in the studies. P (○), PBT-3 (●), PBT-6 (▲) (e/R = 0.57). PBT (△) (e/R = 0.43, d/D = 0.5).

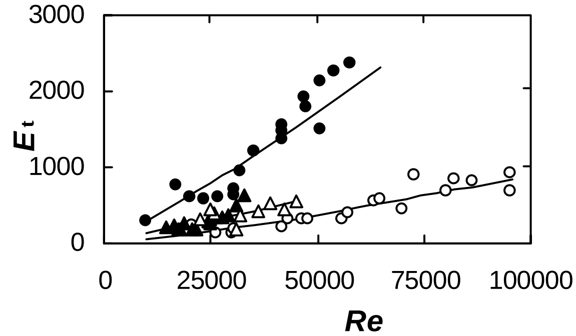

Fig. 7. Comparison of the dependence $E_{\mathrm{t}} = f(Re)$ for different eccentric impellers used in the studies. P (○), PBT-3 (●), PBT-6 (▲) (e/R = 0.57). PBT (△) (e/R = 0.43, d/D = 0.5).

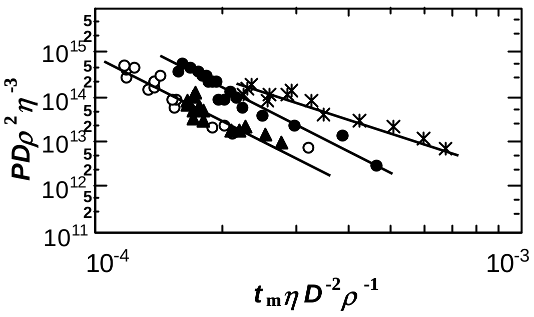

Fig. 8. Comparison of the dependence $(PD\rho^2/\eta^3) = f(t_{\mathrm{m}}\eta/(D^2\rho))$ for different impellers; d/D = 0.33; e/R = 0 (P (∗)) or e/R = 0.57 (P (○)); PBT-3 (●); PBT-6 (▲).

$E_{\mathrm{t}} = f(Re)$, this physical parameter is ascribed to the Re number only.

Dimensionless relationship $PD\rho^2/\eta^3 = f(t_{\mathrm{m}}\eta/D^2\rho)$ proposed by *Zlokarnik* [2, 5] could also be calculated for centrally and eccentrically located propeller and pitched blade turbines. The results are presented in Fig. 8. Assuming constant value of the modified mixing number $t_{\mathrm{m}}\eta/D^2\rho$, the highest modified power number $PD\rho^2/\eta^3$ corresponds to the centric propeller, whereas the lowest one to the eccentric three-blade propeller and pitched blade turbine with diameter d = 0.33 D.

The dependences $E_{\mathrm{m}} = f(Re)$, $\Theta = f(Re_{\mathrm{P,V}})$, $E_{\mathrm{t}} = f(Re)$, and $PD\rho^2/\eta^3 = f(t_{\mathrm{m}}\eta/D^2\rho)$ presented in Figs. 5—8 have been approximated by means of the following equations

$$E_{\mathrm{m}} = Pt_{\mathrm{m}} = A_1 Re^{B_1} \tag{6}$$

for $Re \in \langle 1 \times 10^4; 9.6 \times 10^4 \rangle$

$$\Theta = nt_{\mathrm{m}} = A_2 \left(Re_{\mathrm{P,V}}\right)^{B_2} = A_2 \left(\frac{\left(\frac{P}{V}\right) D^4 \rho^2}{\eta^3} \right)^{B_2} \tag{7}$$

for $Re_{\mathrm{P,V}} \in \langle 3 \times 10^{12}; 8.8 \times 10^{14} \rangle$,

$$E_{\mathrm{t}} = \frac{Pt_{\mathrm{m}}^3}{\rho D^5} = A_3 Re^{B_3} \tag{8}$$

for $Re \in \langle 1 \times 10^4; 9.6 \times 10^4 \rangle$
and

$$\frac{PD\rho^2}{\eta^3} = f\left(\frac{t_{\mathrm{m}}\eta}{D^2\rho}\right) = A_4 \left(\frac{t_{\mathrm{m}}\eta}{D^2\rho}\right)^{B_4} \tag{9}$$

for $t_{\mathrm{m}}\eta/(D^2\rho) \in \langle 1 \times 10^{-4}; 7 \times 10^{-4} \rangle$.

The coefficients A_1—A_4 and exponents B_1—B_4 in eqns (*6*—*9*), as well as the approximation errors $\pm\Delta$ are given in Table 3.

Comparison of the mixing energy E_{m} and E_{t} in Figs. 5 and 7 for different eccentric agitators shows that the propeller requires the lowest mixing energy needed to obtain a given value of the mixing time, t_{m}, at a given level of liquid turbulence (Re = const). Therefore, eccentric propeller (e/R = 0.57) can be recommended for liquid homogenization in the unbaffled agitated vessel. The results shown in Fig. 8 also suggest that eccentric propeller is advantageous for liquid homogenization in the unbaffled agitated vessel. Taking into account criterion (*1*) proposed by *Zlokarnik* [5], different agitators can be compared more precisely. Namely, for assumed working volume of the agitated vessel and a liquid with given physical properties, that agitator is better for which required mixing time, t_{m}, is reached with the minimum mixing energy, E_{m}.

Using three different comparative criteria (eqns *1*—*3*) it can be stated that, out of the agitators tested in the study, eccentric propeller (e/R = 0.57) enables to obtain the highest efficiency of the liquid homogenization within the turbulent regime of the Newtonian liquid in the unbaffled agitated vessel. Good results obtained for eccentric propeller compared with different pitched blade turbines are related with the characteristic flow pattern for this agitator. Propeller generates exactly axial liquid flow which advantageously affects liquid homogenization in the agitated vessel.

Table 3. Values of Parameters in Eqns (*6—9*)

Impeller type		P	P	PBT-3	PBT-6	PBT
	d/D	0.33	0.33	0.33	0.33	0.5
	Z	3	3	3	6	3
	e/R	0	0.57	0.57	0.57	0.43
Eqn (*6*)	A_1	–	10^{-9}	9×10^{-9}	9×10^{-9}	2×10^{-7}
	B_1	–	2.35	2.34	2.34	1.96
	$\pm\Delta$ %	–	11	14	20	15
Eqn (*7*)	A_2	–	0.67	0.67	0.44	0.23
	B_2	–	0.14	0.14	0.14	0.14
	$\pm\Delta$ %	–	10	5	7	10
Eqn (*8*)	A_3	–	4×10^{-4}	1.05×10^{-2}	1.23×10^{-2}	1.23×10^{-2}
	B_3	–	1.27	1.11	1	1
	$\pm\Delta$ %	–	15	15	17	17
Eqn (*9*)	A_4	2×10^{4}	10^{-4}	8.5×10^{-3}	10^{-4}	–
	B_4	−2.73	−4.72	−4.4	−4.72	–
	$\pm\Delta$ %	22	21	23	23	–

SYMBOLS

d	diameter of the agitator	m
D	inner diameter of the agitated vessel	m
e	eccentricity of the agitator shaft	m
E_m	mixing energy	J
E_t	dimensionless mixing energy defined by eqn (*2*)	
h	off-bottom clearance of the agitator	m
H	liquid height in the vessel	m
n	agitator speed	s^{-1}
Ne	power number ($= P/(n^3d^5\rho)$)	
P	power consumption	W
r	radial coordinate	m
R	inner radius of the vessel ($R = D/2$)	m
Re	Reynolds number ($Re = nd^2\rho/\eta$)	
$Re_{\mathrm{P,V}}$	modified Reynolds number ($Re_{\mathrm{P,V}} = [(P/V)D^4\rho^2]/\eta^3$)	
S	pitch of the propeller agitator	m
t_m	mixing time	s
V_a	volume of the tracer pulse added	m^3
V_L	total volume of the liquid	m^3
z	axial coordinate	m
Z	number of impellers blades	
β	pitch of the propeller blade	°
ε	specific mixing energy	W kg^{-1}
ε_V	specific mixing energy	W m^{-3}
η	dynamic viscosity	Pa s
φ	angle coordinate	°
ρ	density	kg m^{-3}
Θ	dimensionless mixing time ($= nt_\mathrm{m}$)	

REFERENCES

1. Nagata, S., *Mixing. Principles and Applications.* Kodansha, Tokyo, 1975.
2. Stręk, F., Agitation and Agitated Vessels. Wydawnictwa Naukovo-Techniczne, Warsaw, 1981 (in Polish).
3. Gogate, P. R. and Pandit, A. B., *Can. J. Chem. Eng. 77*, 988 (1999).
4. Patil, S. M., Gogate, P. R., Patwardhan, A. W., and Pandit, A. B., *International Symposium on Mixing in Industrial Processes ISMIP4.* Toulouse, 2001.
5. Zlokarnik, M., *Chem.-Ing.-Tech. 39*, 539 (1967).
6. Novak, V. and Rieger, F., *IChemE, Symp. Series 136*, 511 (1994).
7. Fort, I., Jirout, T., Rieger, F., Allner, R., and Sperling, R., *15th International Congress CHISA*, Prague, 2002.
8. Shaw, J. A., *Chem. Eng. Prog. 9*, 45 (1994).
9. Herbert, R. M., Knobling, K., and Post, T., *Chem-Tech.* (Heidelberg) *23*, 40 (1994).
10. Ruszkowski, S. W., *IChemE, Symp. Series 136*, 283 (1994).
11. Rieger, F. and Rzyski, E., *Inż. Ap. Chem. 6*, 13 (1998).
12. Dyląg, M. and Brauer, H., *Verfahrenstechnik 10*, 637 (1976).
13. Karcz, J. and Cudak, M., *Chem. Pap. 56*, 382 (2002).
14. Cudak, M., *PhD. Thesis.* Technical University of Szczecin, 2004.
15. Rzyski, E., *Inż. Chem. Proc. 2*, 379 (1981).
16. Medek, J. and Fort, I., *5th European Conference on Mixing.* Wuerzburg, 1985.
17. King, R. and Muskett, M. J., *5th European Conference on Mixing*, Wuerzburg, 1985.
18. Seichter, P., Pesl, L., Slama, V., and Mazoch, J., *14th International Congress CHISA*, Prague, 2000.
19. Karcz, J. and Szoplik, J., *Chem. Pap. 58*, 9 (2004).
20. Karcz, J., Cudak, M., and Szoplik, J., *Chem. Eng. Sci. 60*, 2369 (2005).
21. Karcz, J. and Szoplik, J., *Inż. Chem. Proc. 22*, 651 (2001).
22. Szoplik, J., *PhD. Thesis.* Technical University of Szczecin, 2004.