INVESTIGATION OF THE HOMOGENIZATION EFFICIENCY OF VARIOUS PROPELLER AGITATOR TYPES

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Ship screws and airscrews, widely known under the name propellers, have the common characteristic that the profiles formed by the propeller blades with the cylinder surfaces, concentric with the rotational axis but of different radii, include with the plane perpendicular to the rotational axis different, so-called adjustable or geometrical angles of pitch. Proceeding from the angle of pitch towards the end of the propeller blade, these angles of pitch continuously decrease for reasons well known from the literature [1], the propeller blade is quasi twisted. In certain fields of application of propellers used in liquids and gases (ship screw, airscrew), where propulsion efficiency is an aspect of primary importance, propellers are designed with carefully selected blade profiles. On the other hand, there are fields of application, such as stirring of liquids in the chemical industry, small ventilators, etc., where a slight reduction of efficiency is a somewhat negligible aspect. Here, the use of profiles similar to aircraft blade sections is already unjustified, and a profile bent from plate can also be well used. It can be established at the same time that the profile made of plate, owing to its relative thinness, is more advantageous even from the point of view of efficiency than a blade profile of greater thickness in the case of the relatively low Reynolds numbers usual in these fields.

The main advantage of propellers made of plate over those made by other working, casting methods, is their substantially less weight, which advantageously affects the critical speed of the agitator shaft, particularly in stirring liquids in the chemical industries. Besides the advantages mentioned, however, propellers made of plate have at the same time the considerable disadvantage of being difficult to manufacture. Already the pattern needed for bending curved and at the same time twisted, is rather expensive, while the simple flexure of the plate makes manufacture difficult because of the necessary local stretching. Problems were finally solved by the application of a design principle, on the basis of which the French company S.E.M.

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*Hungarian Chemical Industries Design Center and the Hungarian Chemical Industries Design Center (VEGYTERV) developed two propeller agitators of extremely different form.

In the first part of the present communication the design principle of the plate propeller agitator developed by VEGYTERV will be discussed, while in the second part the homogenization efficiency of the plate propeller agitator will be compared to those of the Hungarian standard propeller made by casting technology, of the 6-blade open-style 45° pitched blade turbine agitator and of the propeller agitator developed by S.E.M.

Design principle of propellers with circular cylindrical surface

The design principle discussed in the following makes possible the development of a propeller blade, which, in spite of meeting twisting requirements, can be made of plate fitting a circular cylindrical surface.

Figure 1 shows the outline of the projection of a propeller of conventional design on the plane perpendicular to its rotational axis. The trajectories of the intersection of the circular cylindres with various radii r_1, concentric with the rotational axis, represented in this projection by circular arcs of radius r_i, are shown in the same figure. The basic design principle of propellers operating in liquids is represented by the following relationship:

$$s = 2\, r_i \cdot \pi \cdot \mathrm{tg}\, \varphi_i\,, \tag{1}$$

where s is the geometrical pitch of the propeller in the direction of the rotational axis during a complete turn-around. Its value for a given propeller is constant in the majority of cases. φ_i is the adjustable angle of the sections cut out by cylinder surfaces of different radii r_i.

A generatrix of each circular cylinder of radius r_i intersects the inlet and the outlet edge, respectively, of the propeller blade. The intersection with the inlet edge is marked a, the intersection with the outlet edge b in Fig. 1. These two points form each a point of the helical line of pitch angle

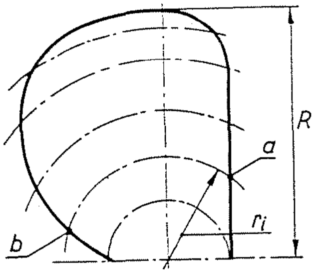


Fig. 1. Front view outline of propeller blade

φ_i of the circular cylinder of radius r_i. If the circular cylinder of radius r_i is made to intersect the surface of a circular cylinder of radius R_h in appropriately selected steric position, there will always be two points along the penetration space curve of the two cylindres, the mutual steric position of which is the same as that of points a and b, located on the circular cylinder of radius r_i. These points found are marked a' and b' on the perspective Fig. 2. These points are determined according to the known rules of space geometry. The determination is easier if the axes of the two circular cylinders are arranged perpendicular to one another. Section $a'-b'$ of the common penetration curve of the two circular cylinders is a section of the propeller blade. If the extreme points of the penetration curves are determined by means of concentric circular cylinders of different radii r_i in a number sufficient for construction, and the points are connected, then the outline of the propeller blade, transformed to a circular cylinder of radius R_h, is obtained. This transformation can be performed also when the propeller blade is not constructed according to the basic relationship mentioned above, namely when not only φ_i but s is also changing with changing r_i. The curvature of the profile of

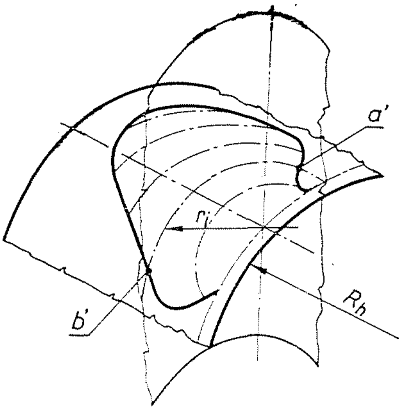


Fig. 2. Transformed diagram of propeller blade outline

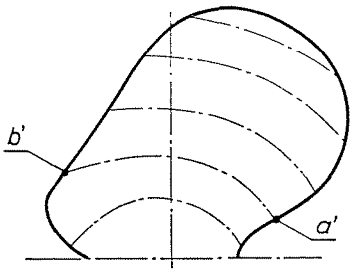


Fig. 3. Rolled out picture of propeller blade outline

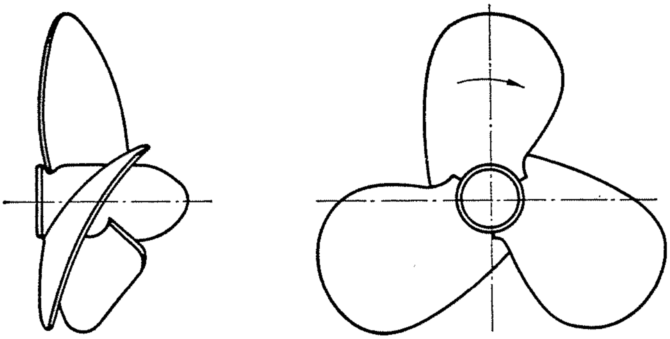
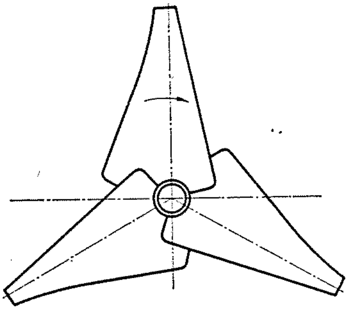


Fig. 4. Side and front views of VEGYTERV propeller



5. *Fig.* Front view of S.E.M. propeller

the propeller blade depends also on the ratio of radius R to that of the bending circular cylinder. In many cases the ratio $R/R_h = 1$ can be well used for practical purposes. In our experiments too, a plate propeller agitator of such ratio ($R/R_h = 1$) has been used.

Suitably, construction will begin by plotting the front view projection according to Fig. 1, the outline of which can be arbitrary, under consideration of practical purposes. Figure 3 shows the picture of the propeller blade rolled out on the plane as a result of such a construction, while Fig. 4 the side view and the front view of the finished propeller. A characteristic of the plate propeller agitator designed in this way is the low lateral ratio of the blades, i.e. its short, broad form.

Figure 5 shows front view of the plate propeller developed by the French company S.E.M., constructed on the same design principle as the propeller described above, but having a considerably different external form. It is characterized by trapeziform blades of high lateral ratio, for which it is called also "sabre-blade" propeller. Its diameter is in most of the cases 70% of the diameter of the vessel.

In addition to the two plate propellers discussed above, several propellers of different design can be constructed on the same principle, the suitability of which for a given operation will be determined by experimental measurements.

Homogenization efficiency of agitators

The homogenization efficiency of agitators can be estimated on the basis of homogenization time and power consumption. That agitator will be the more efficient, which realizes the required degree of homogeneity in the present time at a lower energy consumption ($N \cdot \tau$).

The power consumption of the agitators and homogenization time have been determined in the pilot-plant laboratory of the Department of Chemical Unit Operations of the Technical University, Budapest.

Experimental apparatus

Experiments were carried out in a tank of $D = 396$ mm diameter with basket-curve bottom and in a tank of $D = 529$ mm with plain bottom. The height of the resting liquid level in the tank was the same as the diameter of the tank. In each instance a baffled tank was used for the experiments, because orientative experiments showed homogenization efficiency to be considerably worse without baffles. Four vertical, equally spaced baffles of width $w = 0.1\ D$ were placed in the vessel adjacent to the wall. Dimensions and geometrical ratios of the agitators are contained in Table 1, material characteristics of the liquids mixed in Table 2.

Table 1

Geometrical ratios of the agitators investigated

Agitator	d mm	d/D	b/d	s/d	$h =$
6-blade open-style pitched blade turbine, $\alpha = 45°$	133	0.250; 0.333	0.177	—	d; $\frac{H}{2}$
Standard propeller	133	0.250	0.30	1.14	d
S.E.M. propeller	375	0.710	—	0.58	$\frac{H}{2}$
VEGYTERV propeller	133	0.250	—	1.05	d
	101 201 282	0.254 0.382; 0.508 0.534; 0.713	— — —	0.94 1.00 0.99	$\frac{H}{2}$

Table 2

Material characteristics of the liquids at 25 °C

Symbols in Figs 6 and 9	liquid	$\mu \cdot 10^3$ (kg/m · s)	ϱ (kg/m^3)
◑	sugar solut.	221	1334
⊗	molasses	53.0	1306
▲	molasses	20.0	1240
+	molasses	7.15	1189
▽	molasses	4.50	1030
□	water	0.894	997

Power consumption of the agitators

The power consumption of agitators has been measured in a mixer equipped with balance motor. Measuring equipment and method have been described in detail in earlier communications [2, 3].

Results have been plotted in an Euler—Reynolds diagram (Fig. 6).

It has been established on the basis of these measurements that in the turbulent range (Re $> 10^4$) the Euler number is independent to the Reynolds number in tanks equipped with baffles. The Euler number of the agitators is given in Table 3.

The Euler numbers of the 6-blade open-style 45° pitched blade turbine and of the standard propeller agree with those published in the literature [4].

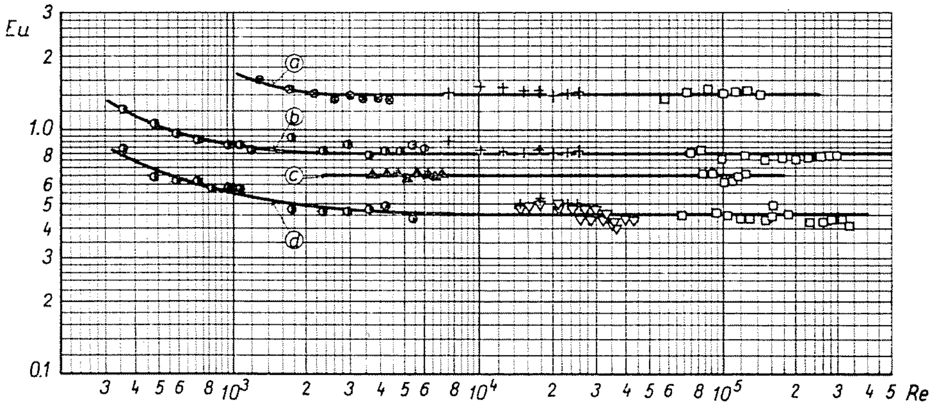


Fig. 6. Power consumption of axial mixers in baffled tanks: H = D, $w = 0{,}10 \cdot D$; $i = 4$ a) 6-blade 45° turbine agitator: $D = 529$ mm, $d = 133$ mm; $h = 133$ mm; b) 3-blade VEGYTERV propeller: $D = 529$ mm; $d = 133$ mm; $s/d = 1.05$; $h = 133$ mm; c) 3-blade VEGYTERV propeller: $D = 396$ mm, $d = 101$ mm, $s/d = 0.94$ mm, $h = 198$ mm; d) 3-blade standard propeller: $D = 529$ mm, $d = 133$ mm, $s/d = 1.14$, $h = 133$ mm

Table 3

Power consumption of the agitators
$Re = 10^4 \ldots 2.10^5$, $i = 4$, $w/D = 0.10$, $H = D$

Agitator	d/D	h	$Eu \pm 95\,\%$ Confidence int.
6-blade open-style pitched blade turbine, $\alpha = 45°$	0.250	d	1.41 ± 0.02
	0.333	d	1.50 ± 0.06
	0.333	$0.5 \cdot H$	1.38 ± 0.03
Standard propeller	0.250	d	0.43 ± 0.01
S.E.M. propeller	0.710	$0.5 \cdot H$	0.098 ± 0.006
VEGYTERV propeller	0.250	d	0.78 ± 0.01
	0.254	$0.5 \cdot H$	0.65 ± 0.01
	0.382		0.68 ± 0.01
	0.508		0.68 ± 0.01
	0.534		0.70 ± 0.01
	0.713		0.80 ± 0.02

No data were found in the literature on the Euler number of the S.E.M. propeller agitator.

The Euler number of the plate propeller agitator designed by VEGYTERV has been measured for an installation height of $h = H/2$ at different d/D values. For $d/D = 0.25 \ldots 0.50$ the value of the Euler number is nearly constant ($Eu = 0.68$), for $d/D > 0.5$ the value of the Euler number increases in a measure identical with that of the standard propeller [5].

Measurement of homogenization time

Three methods are known from literature for the measurement of homogenization time. All three methods have in common that a pulse disturbance is caused by adding usually a small amount of substance instantaneously to the liquid content of the tank. The methods differ with respect to the variables measured:

a) measurement of conductivity, when electrolyte is added to the liquid in the tank [6...22],

b) measurement of temperature, when heat is introduced into the liquid [13, 23...29],

c) colorimetry, when the colour change of an indicator, produced by acid–base reaction is measured [9, 13, 24, 26...34].

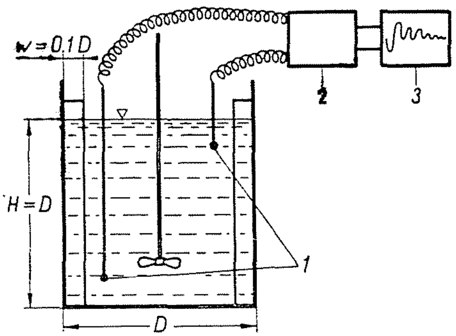


Fig. 7. Mixing equipment. 1. Thermistors, 2. Wheatstone bridge. 3. Line chart compensograph

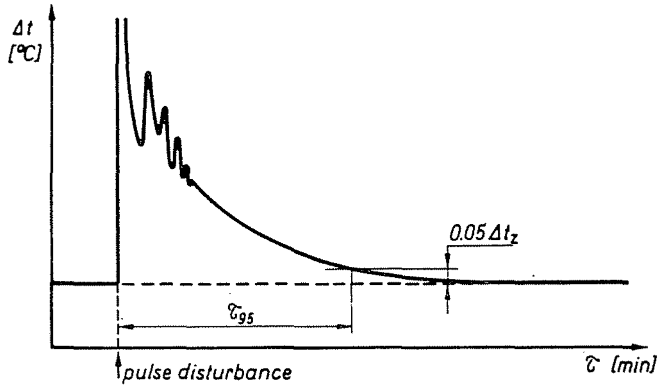


Fig. 8. Explanatory figure for the determination of homogenization time

Of these three methods, the thermal pulse disturbance method according to b) has been found the most suitable, and this method was used in our experiments.

Two thermistors of high sensitivity and small time constant were diagonally placed in the tank. The upper thermistor was located 50 mm below the liquid level at a distance of 60 mm from the wall of the tank, while the lower thermistor at a distance of 60 mm both from the wall and the bottom of the tank. The thermistors were connected in opposite circuits of a Wheatstone-bridge and the temperature difference was measured (Fig. 7). A detailed description of the measurements and the definition of the degree of homogeneity are found in an earlier work [35].

In our experiments, homogenization time belonging to a degree of homogeneity of 95% has been determined in the way shown in Fig. 8.

To check the reliability of our measuring method, a few experiments were repeated with four thermistors located in the tank. Data obtained in this way agreed with those obtained with two thermistors. This is in agreement with findings published in the literature [7, 8, 9, 14], according to which neither the temperature and the place of disturbance, nor the location of the measuring point have a considerable effect on homogenization time in the turbulent range. Therefore, two thermistors were used in our subsequent experiments.

Homogenization number, the product of homogenization time and of the speed of rotation of the agitator, has been plotted as a function of the Reynolds number (Figs 9 a, b, c). It is seen from the diagram that the dimensionless homogenization number is independent of the Reynolds number in the turbulent range ($Re > 10^4$).

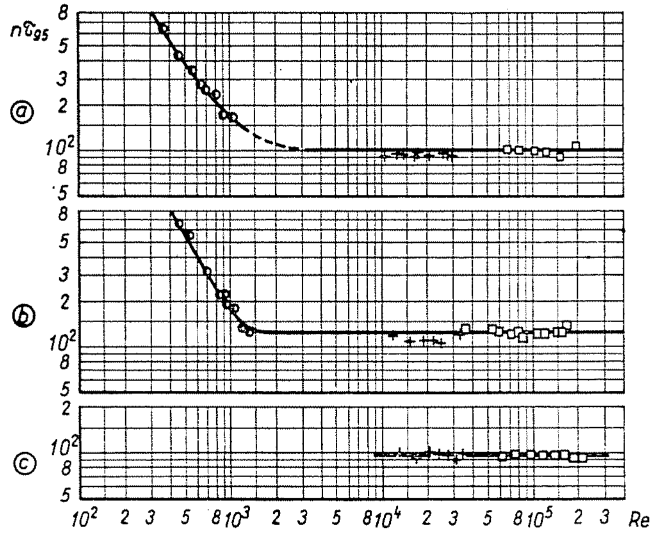


Fig. 9. Homogenization number of axial mixers in baffled tanks: $D = 529$ mm; $d = 133$ mm, $h = d$, $H = D$, $w = 0.1 \cdot D$, $i = 4$, a) 3-blade VEGYTERV propeller, $s/d = 1.05$, b) 3-blade standard propeller, $s/d = 1.14$, c) 6-blade 45° turbine agitator

The homogenization number of the agitators investigated is given in Table 4. The homogenization number of the VEGYTERV propeller agitator has been investigated as a function of the diameter ratio D/d. The equation fitting best measured data has been determined in the form of a power product by weighted regression. The relationship obtained is:

$$n\ \tau_{95} = 4.43\ (D/d)^{2.24} \tag{2}$$

number of repetitions: 90
number of measuring points: 4

The goodness of fit has been checked by F-test. The critical F-value for 95% one-sided significance level at degrees of freedom 2 and 86 is 3.1.

Table 4

Homogenization number and homogenization efficiency of the agitators in the turbulent range $Re > 10^4$; $\tau \cdot \mu / D^2 \varrho < 6.10^{-4}$; $i = 4$; $w/D = 0.10$; $H = D$

Agitator	$\frac{d}{D}$	h	$n\,\tau_{95} \pm 95\,\%$ confidence int.	$K_T \pm 95\%$ confidence int.
6-blade open-style pitched blade turbine $\alpha = 45°$	0.250	d	98 ± 3.3	$1.3 \cdot 10^3 \pm 0.1 \cdot 10^3$
	0.333	d	82 ± 12	$3.4 \cdot 10^3 \pm 1.0 \cdot 10^3$
	0.333	$0.5 \cdot H$	62.5 ± 9.6	$1.4 \cdot 10^3 \pm 0.6 \cdot 10^3$
Standard propeller	0.250	d	122 ± 4	$9.6 \cdot 10^2 \pm 2 \cdot 10^2$
S.E.M. propeller	0.710	$0.5 \cdot H$	31 ± 1.6	$5.0 \cdot 10^2 \pm 0.8 \cdot 10^2$
VEGYTERV propeller	0.250	d	100 ± 2.5	$7.8 \cdot 10^2 \pm 0.5 \cdot 10^2$
	0.254	$0.5 \cdot H$	97 ± 8	$6.3 \cdot 10^2 \pm 1.7 \cdot 10^2$
	0.382		36 ± 8	$2.6 \cdot 10^2 \pm 1.6 \cdot 10^2$
	0.508		22 ± 8	$2.5 \cdot 10^2 \pm 1.6 \cdot 10^2$
	0.534		18 ± 8	$1.8 \cdot 10^2 \pm 1.6 \cdot 10^2$
	0.713		14 ± 6	$4.0 \cdot 10^2 \pm 1.7 \cdot 10^2$

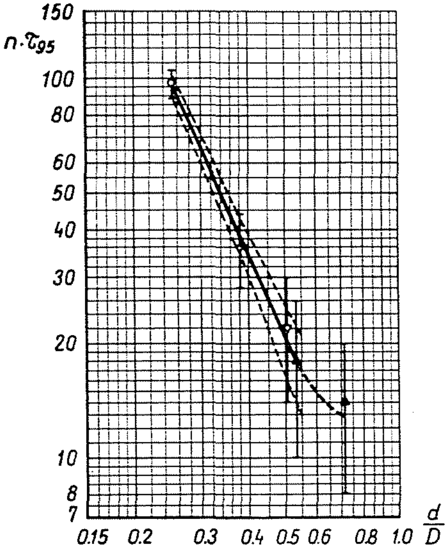


Fig. 10. Dependence of homogenization number on diameter ratio in the case of the VEGYTERV propeller ($h = \frac{H}{2}$; $H = D$; $i = 4$; $w = 0.1 \cdot D$; $Re > 10^4$) ○ — $d = 101$ mm; ▽ — $d = 201$ mm; ▲ — $d = 282$ mm

This is higher than the ratio of residual mean square error and of mean square error calculated from the repetitions (2.8), so that the dependence of the homogenization number on the diameter ratio is appropriately described by Eq. (2). Equation (2) is represented in Fig. 10 by a continuous line, its $\pm 95\%$ confidence interval by a broken line, while the perpendicular lines drawn to the single measuring points mark the $\pm 95\%$ confidence interval of the points.

The dependence of the homogenization number of the standard propeller on the ratio D/d has been investigated by several authors [6, 7, 8, 10, 11, 21]. The exponent of the D/d ratio varies in the single works in the range from 1.93 to 2.05. The difference between data in the literature relevant to the standard propeller and the value of 2.24 valid for the VEGYTERV propeller is not significant.

Homogenization efficiency of the agitators

For the comparison of the homogenization efficiency of agitators, dimensionless expressions have been introduced, which comprise — besides the tank diameter and the physical characteristics of the liquid mixed — only homogenization time ($\tau_{95} \cdot \mu/D^2\varrho$) and energy consumption of homogenization ($N \cdot \tau_{95} \cdot \varrho/D\mu^2$). The expressions can be calculated from the following dimensionless quantities:

$$\frac{(N \cdot \tau_{95})\varrho}{D \cdot \mu^2} = Eu\, Re^2\, (n \cdot \tau_{95}) \cdot \left(\frac{d}{D}\right) \tag{3}$$

$$\frac{\tau_{95} \cdot \mu}{D^2 \cdot \varrho} = (n \cdot \tau_{95})\, Re^{-1} \left(\frac{D}{d}\right)^2 \tag{4}$$

Since in the turbulent region both Euler number and homogenization number are independent of the Reynolds number, it can be written on the basis of Eqs (3) and (4):

$$\frac{(N \cdot \tau_{95})\,\varrho}{D \cdot \mu^2} = K_T \left(\frac{\tau_{95} \cdot \mu}{D^2 \cdot \varrho}\right)^{-2} \tag{5}$$

where

$$K_T = Eu\, (n \cdot \tau_{95})^3 \left(\frac{d}{D}\right)^5 \tag{6}$$

K_T is suitable for classifying of agitators according to their homogenization efficiency, as it has been proved by several authors [2, 3, 7, 9, 11, 24, 27] that in geometrically similar equipment the values of both Euler number and homogenization number are identical. That agitator will be the more efficient, which has a lower K_T value. K_T values of the agitators investigated are given in Table 4 and Fig. 11.

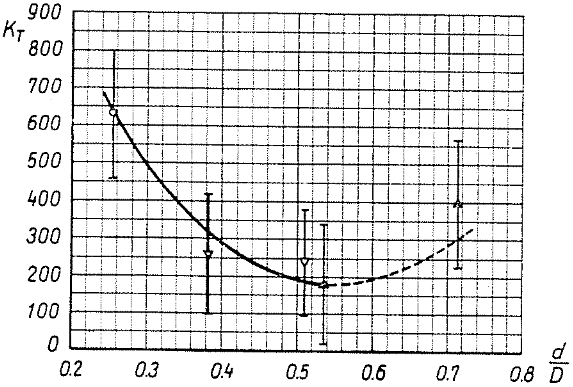


Fig. 11. Homogenization efficiency of the VEGYTERV propeller as a function of diameter ratio ($h = \frac{H}{2}$; $H = \mathrm{D}$; $i = 4$; $w = 0.1 \cdot \mathrm{D}$; $\mathrm{Re} > 10^4$) ○ — $d = 101$ mm; ▽ — $d = 201$ mm; ▲ — $d = 282$ mm

Similar results were obtained by LANDAU [15], who investigated turbine agitators with straight blades and blades with an angle of inclination of 45°, and propeller agitators at diameter ratios of $D/d = 3\ldots10$. He found that the straight blade turbine agitator is the least efficient, while the cast propeller agitator with square pitch is the most efficient. An increase in d/D ratio increases homogenization efficiency.

Results

At a given homogenization time and degree of homogenization:

— among the agitators investigated the 6-blade open-style pitched blade turbine agitator ($\alpha = 45°$) has the highest energy consumption, and is thus the least efficient;

— the standard propeller requires by about 25% less energy than the 6-blade, 45° turbine agitator;

— of the propeller agitators, the VEGYTERV propeller is the most efficient at identical diameter ratio;

— optimum diameter ratio for the VEGYTERV propeller is $d/D \simeq 0.55$.

Summary

The propeller agitator designed and constructed by Hungarian Chemical Industries Design Center has been compared with the "sabre-blade" propeller agitator of the company S.E.M., with the standard propeller agitator manufactured by casting, and with the 6-blade open-style 45° pitched blade turbine agitator. Power consumption and homogenization time of the agitators have been measured, the latter by the thermal pulse disturbance method.

It has been established that the VEGYTERV propeller agitator has the highest homogenization efficiency, its optimum agitator to tank diameter ratio being 0.55.

Symbols

D	diameter of tank, [m]
d	diameter of agitator, [m]
H	height of liquid level in the tank, [m]
h	distance of the agitator from the bottom of the tank, [m]
i	number of baffles, —
K_T	constant in Eq. (5), —
N	power consumption of the agitator, [W]
n	speed of rotation of the agitator, [l/s]
R	radius of propeller agitator, [m]
R_h	radius of bending circular cylinder (see Fig. 2), [m]
r_i	see Eq. (1) and Figs 1 and 2
s	pitch of propeller agitator, [m]
Δt_z	change in temperature of the liquid content of the tank, due to disturbance, [deg.]
w	width of baffle, [m]
X	degree of homogeneity
α	angle of inclination of the turbine blade, [rad]
ϱ	liquid density, [kg/m^3]
μ	viscosity of liquid, [kg/m · s]
τ_X	homogenization time belonging to a degree of homogeneity of X %, [s]
φ	adjusting angle of the section belonging to radius r_i of the propeller blade, [rad]

$Eu = \frac{N}{d^5 n^3 \cdot \varrho}$ Euler number of mixing, —

$n \cdot \tau_X$ homogenization number, —

$Re = \frac{d^2 \cdot n \cdot \varrho}{\mu}$ Reynolds number of mixing, —

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