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MIXER WITH A CENTRAL CIRCULATING TUBE

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Abstract

The hydrodynamic properties of a mixer with a central circulating tube were studied. Mixed contents were created from different liquids: water, water – saccharose and water – glycerine, from two-phase mixtures: water – air, water – glass spheres and from three-phase mixtures: water – air – glass spheres.

A new functional relationship was proposed between the energy consumption and Re number for the mixing – homogenization process and it was successfully used in the evaluation of measurement results. It was possible to describe the complete suspension of glass particles in water by Rieger's Π criterion, which was also suitable for describing the mixing process of the three-phase mixture.

Keywords: mixer equipment, circulation tube, power number, one, two and three-phase flows respectively, homogenization times, total solid suspension

1. Introduction

In the food and chemical industries it is often necessary to homogenize various two- and three-phase mixtures (solutions) with a liquid as the continuum phase. Sometimes companies offer tanks for such applications with no built-in parts. In this case good results can be achieved by a mixer with a central circulating tube which may be considered as a type of loop bioreactors, (see Refs. [1] to [4]). For this reason the most appropriate name for this arrangement seems to be a loop mixer. Such a mixer is very effective as far as its homogenization intensity is concerned and baffles are not needed to prevent formation of a central vortex. Moreover, the mixed content shows organized loop motion which can be suitably expressed by well known non-dimensional criteria.

Fig. 1 illustrates this mixer type. The mixing element consists of three blades with an inclination of 45° to the horizontal plane. In *Fig. 1* one can find also the dimensions of the individual mixer part which are in accordance with the previous Czechoslovak Standard [5]. We designed it for a Slovak factory producing machines and equipment for food processing. Our next task was to obtain its main hydrodynamic characteristics in various liquid mixtures.

2. Evaluation of the Quality of Mixing

The properties of a mixer equipment are determined mainly by:

1. the power for the mixing process characterized by Euler's modified criterion [power (Po) number],
2. mixing time needed to obtain a given degree of inhomogeneity (usually the inhomogeneity is supposed to be within ±5% of the given conductivity change, see e. g. [6]),
3. power needed for the mixing of the two-phase water – air system,
4. power which is necessary for the complete suspension of solid particles in a liquid continuum,
5. power needed for the mixing of the three-phase content considering complete suspension of the solid phase in the liquid.

As it is well known, Euler's modified criterion for the turbulent region is expressed by the following relationship:

$$Eu_m = \frac{P}{\rho_l n^3 d_m^5}. \tag{1}$$

The magnitude of criterion (1) can be calculated also from an expression derived by VAVRO on the basis of precise estimation of measurements of several authors [7]. This universal correlation can be written as:

$$Eu_m = \mathrm{Po} = \left[\frac{A_1}{\mathrm{Re}_m} + \frac{A_3}{\mathrm{Re}_m^{(A_4 \mathrm{Re}_m^{A_5})}} + A_6\right]^{\frac{1}{A_2}}, \tag{2}$$

where $A_1 \div A_6$ are parameters depending on the mixer type. *Eq.* (2) considers the types of mixers and vessels and was designed in concordance with the previous Czechoslovak Standard (see e. g. [5] and [8]).

For evaluation of the mixing efficiency, taking into account homogenization times, ZLOKARNIK [9] quotes Hoogendoorn who proposed the following dependence:

$$\frac{P t_m^2}{D^3 \mu} = f\left(\frac{D^2 \rho}{t_m \mu}\right). \tag{3}$$

In [9] also another functional dependence introduced by ZLOKARNIK is given. It is as follows:

$$\frac{P D \rho^2}{\mu^3} = f\left(\frac{t_m \mu}{D^2 \rho}\right). \tag{4}$$

Criterion (3) contains one of the basic parameters, t_m on both sides, while (4) expresses the dependence of power for the mixing on the homogenization time. In our opinion it is more appropriate to look for the dependence of the energy consumed for the homogenization (which is expressed by the term $P t_m$) on the basic hydrodynamic criterion Re. Dimensional analysis performed by Buckingham's theorem has shown that the conditions mentioned above can be expressed by the following relationship:

$$\frac{P t_m \rho}{\mu^2 D} = f(\mathrm{Re}_m), \tag{5}$$

where the modified Reynolds' number is:

$$\mathrm{Re}_m = \frac{n d_m^2 \rho}{\mu}. \tag{6}$$

Here it is also necessary to mention that for the turbulent flow the product

$$n t_m = \mathrm{const}, \tag{7}$$

(see e. g. [6], [7] and [10]).

The power needed for the mixing of the two-phase water – air system can be described most conveniently by Oyama's procedure [11]:

$$\frac{P}{P_g} = f(Na) = f\left(\frac{Q}{n d_m^3}\right). \tag{8}$$

Another correlation suggested by MICHEL and MILLER [6] is given in the following form:

$$P_g = C\left(\frac{P^2 n d_m^3}{Q^{0.56}}\right)^{0.45}, \tag{9}$$

where C is a constant with values within the range of 0.63–1.19. According to [6] $C = 0.72$. Complete suspension of the solid phase in the liquid is expressed by RIEGER by the Π criterion, see [12]:

$$\Pi = \frac{P}{\rho_{\mathrm{mix}}}\sqrt{\left[\frac{\rho_L}{g(\rho_{\mathrm{mix}} - \rho_L)}\right]^3 \frac{1}{D^7}}. \tag{10}$$

ZWIETERING [13] gives a different expression for this phenomenon, but it does not contain the power term. Considerations about this matter can also be found in [14], but they are only descriptive.

Expression (10) can also be used for the description of the three-phase mixing as will be shown in the part about the evaluation of the results of our measurements.

3. Experimental

The mixing equipment described and illustrated above was made of stainless steel. Parameters of its electric motor were: safety voltage 48 V, direct current and $n = 0 \div 30\ \mathrm{s}^{-1}$. The equipment was tested in a glass cylinder with hemispherical bottom.

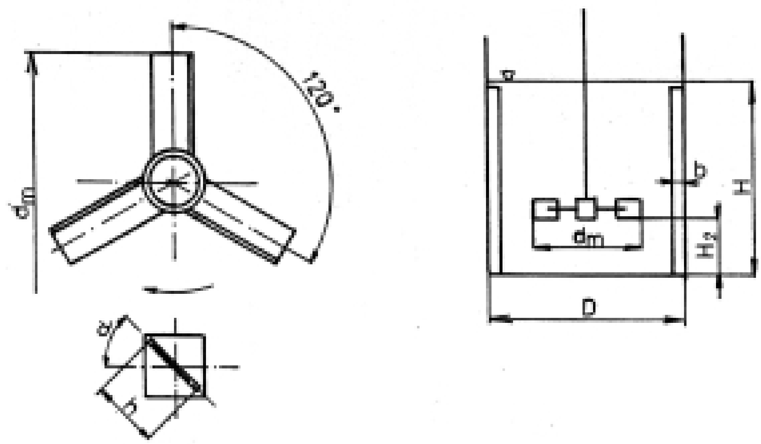

Fig. 1. Dimensions of the main mixer equipment a) $d_m = 76$ mm, $h = 20$ mm, $\alpha = 45°$ b) geometry of the mixing equipment according to [5], number of buffles: 4

The scheme of the experimental equipment is presented in *Fig. 2*. The liquid content was 30 dm^3. In tests for determination of the Po numbers and the homogenization times six different media were used as follows:

distilled water		
saccharose, aqueous solution	0.3	kg/kg
	0.45	kg/kg
	0.5	kg/kg
	0.63	kg/kg
glycerine	0.96	kg/kg.

The physical properties of these solutions are given in *Table 1*.

In the tests with complete suspension of the solid particles the following media were used: tap water (30 dm^3) as the continuum phase and glass spheres with diameters of 0.3 mm, 0.6 mm, 0.8 mm and density 2500 kg/m^3.

Torque moment measurements were performed by a Steiger-Mohilo dynamometer (German product). This device enables to measure with 0.01 Nm accuracy and it measures simultaneously also the frequency of revolutions.

The homogenization signals were produced by a conductivity probe, amplified by a Radelkis conductometer (both Hungarian products) and then transferred to a double line recorder TZ 5000 (Verkon Prague). As a tracer 0.4 ml of saturated NaCl-aqueous solution was used. The resulting conductometric signals were evaluated within ±5% range of the given conductivity change.

Air was introduced through a stainless tube of 8/6 mm diameter, which was formed into an annulus of 120 mm i. d. The air stream was distributed by forty air openings with 0.8 mm diameter. The air flow rate was measured by a rotameter.

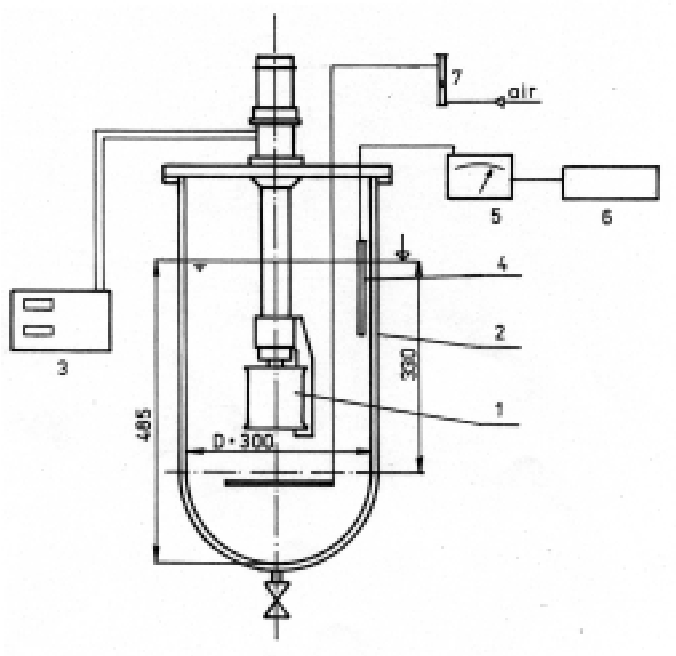

Fig. 2. Scheme of the experimental equipment 1. – the mixer with the central circulating tube, 2 – vessel, 3 – dynamometer, 4 – conductivity probe, 5 – conductometer, 6 – recorder, 7 – rotameter

Table 1. Properties of the tested media

Medium	T [°C]	Dynamic viscosity $\mu \times 10^3$ [Pas]	Density ρ [kg/m^3]
Distilled water	20.1	1.02	998.1
30% wt saccharose – aq. solution	20.0	3.19	1127.0
45%	26.0	8.25	1200
50%	26.0	1543	1230
63%	19.9	100.0	1300
Glycerine	20.0	132.0	1260

The complete suspension of the glass spheres was observed visually and the condition for evaluation of this state was that no particle was staying at the container bottom for more than 2 s (see [6]).

4. Results and Discussion

For the design of the mixer equipment it is necessary to know the Po number. The results of our measurements have shown that in the turbulent region (it begins from about $\mathrm{Re}_m = 2000$) $\mathrm{Po} = 0.98$, see *Fig. 3*. The same type of mixer with similar geometry but without the circulating tube has $\mathrm{Po} = 1.1$ in the turbulent region [8]. Relationship (2) gives $\mathrm{Po} = 1.1$ for this region.

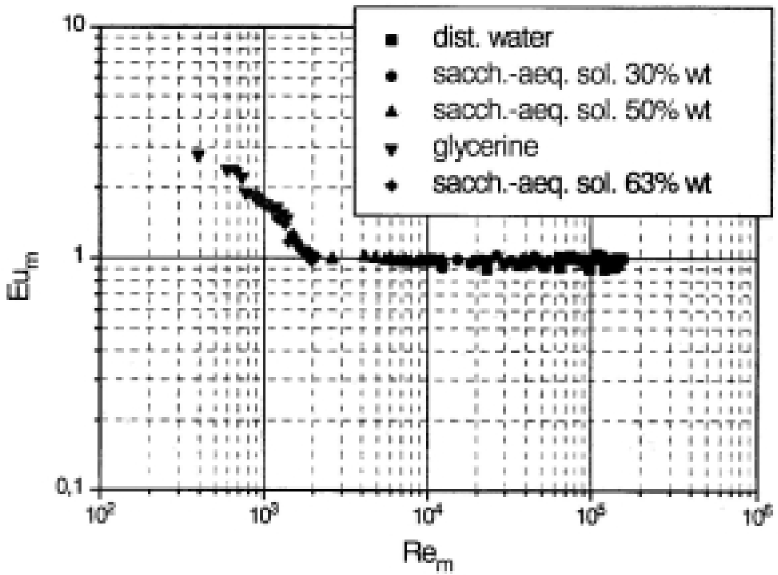

Fig. 3. Graph for $\mathrm{Po} = \mathrm{Eu}_m$ number determination

The test results illustrated in *Fig. 4* confirm the validity of *Eq.* (7) but only for the region where $\mathrm{Re}_m > 2000$ (see *Fig. 5*).

For evaluation of the quality of mixing and the power/energy consumption, relationships (4), (see *Fig. 6*) and (5), (see *Fig. 7*) were used. The data obtained by ZLOKARNIK [9] for a propeller mixer are slightly below the values illustrated in *Fig. 6* but only within the range of $10^{-4} - 3 \times 10^{-3}$. Vice versa, we were not able to describe his results [9] by relationship (5) because of the lack of the individual parameters.

The results of power measurements in the water – air two-phase system are presented in *Fig. 8*. Our tests have shown that Oyama's procedure can be successfully used also in this case. An exception is when the mixer revolution frequency is under $n = 10$. In this case the aeration influences the power drop more slightly

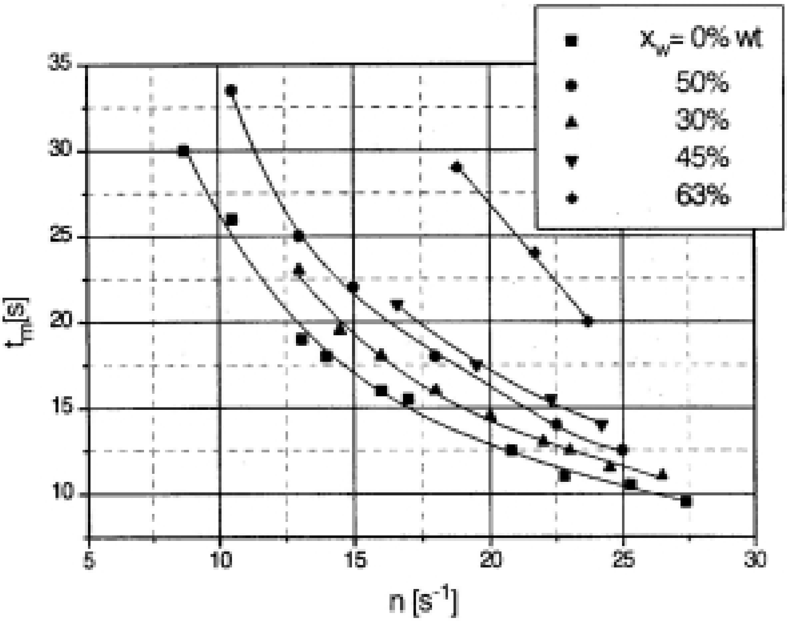

Fig. 4. Homogenization times vs. revolution frequencies for the various solutions

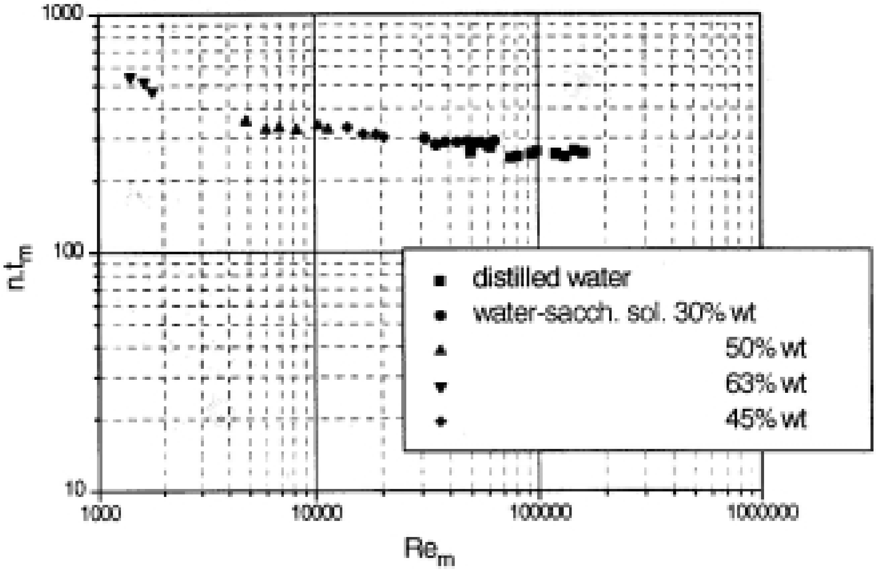

Fig. 5. Dimensionless parameter nt_m as function of Re_m

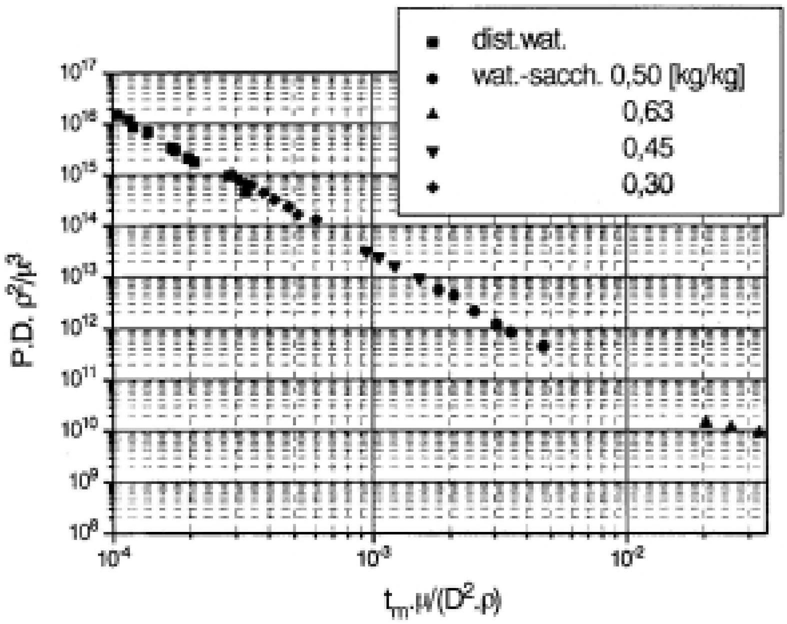

Fig. 6. ZLOKARNIK's (4) evaluation of the efficiency of the mixer equipment

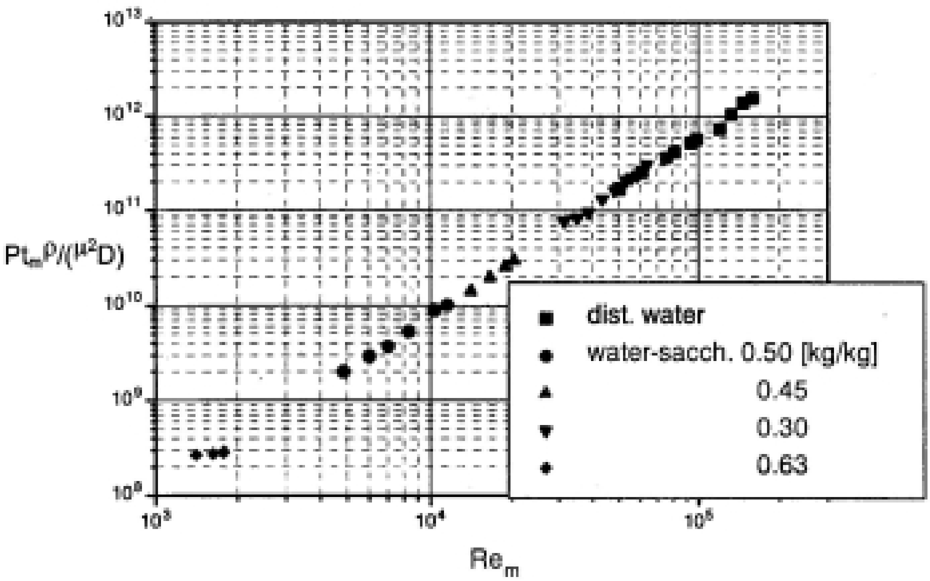

Fig. 7. Evaluation of mixer equipment by criterion (5)

because of the small air flow which is sucked into the central circulation tube. These data are not illustrated in *Fig. 8*.

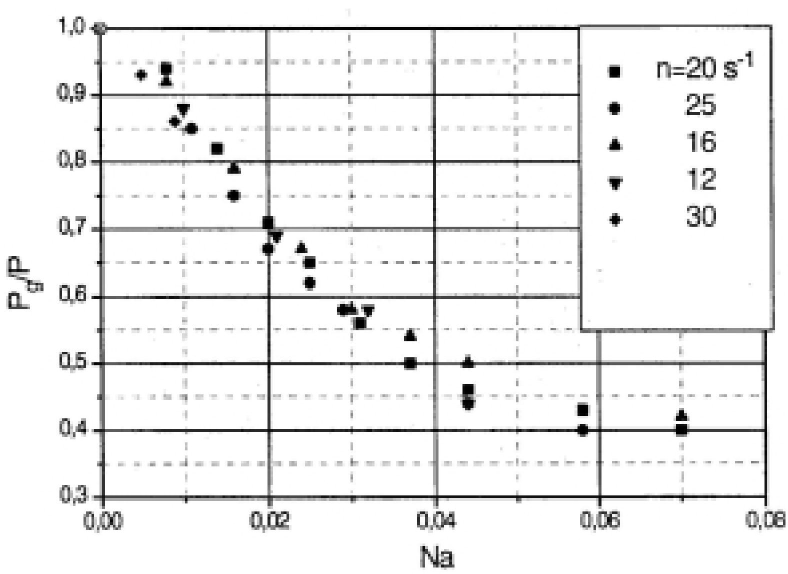

Fig. 8. Power diminishing due to the aeration effect

The results of our measurements describing the complete suspension of the glass spheres are given in *Figs. 9* and *10*. RIEGER's criterion (10) proved to be suitable for the description of such cases.

The measurement results of the three-phase system are illustrated in *Figs.11* and *12*. From these figures it can be seen that for the complete suspension of the glass particles in the presence of air bubbles a higher energy consumption is necessary in comparison with the water – solid phase two-phase system. The explanation of this fact is that in the presence of air the mixed content has a lower density.

5. Conclusions

The hydrodynamic characteristics obtained for the mixer equipment with the central circulating tube pointed out its good properties. The Po numbers were within the range $300 < Re_m < 1.7 \times 10^5$. For the region $Re_m > 2 \times 10^3$ Po equals 0.98 which is approximately about 11% lower compared to the same mixer type located in a geometrically similar vessel with baffles but without the circulating tube (see *Fig. 1b*).

The performed tests proved the correctness of equality (7) for $Re_m > 2000$. Below this value the product (7) is growing. This fact is in concordance with the results of the authors of [9].

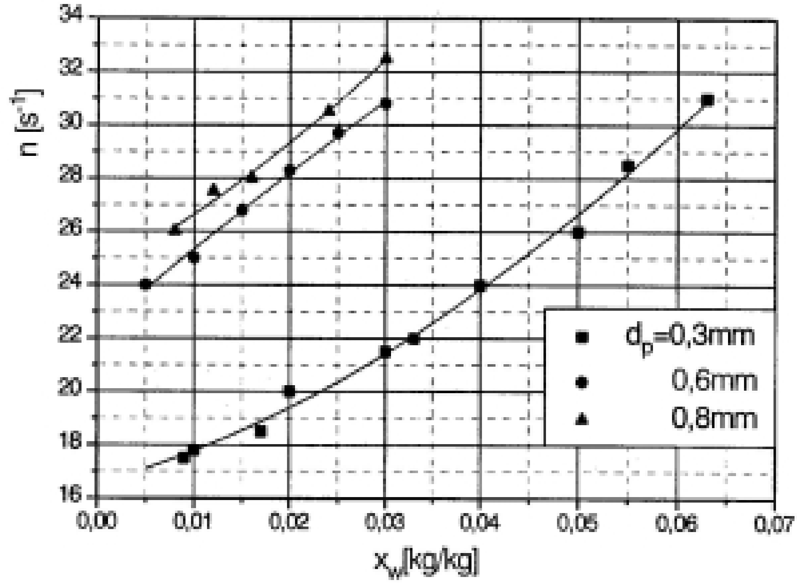

Fig. 9. Total suspension of the water – glass spheres two-phase system

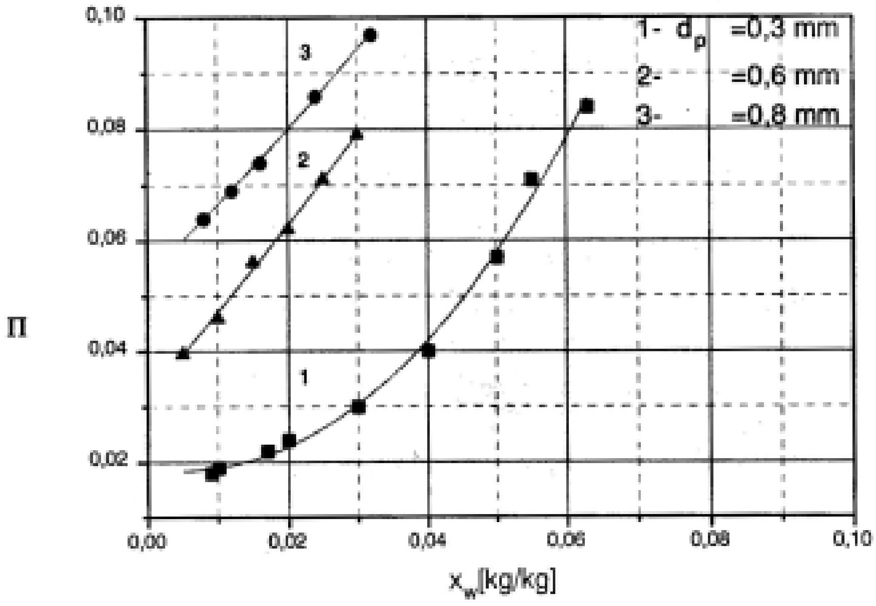

Fig. 10. Total suspension of the water – glass spheres two-phase system

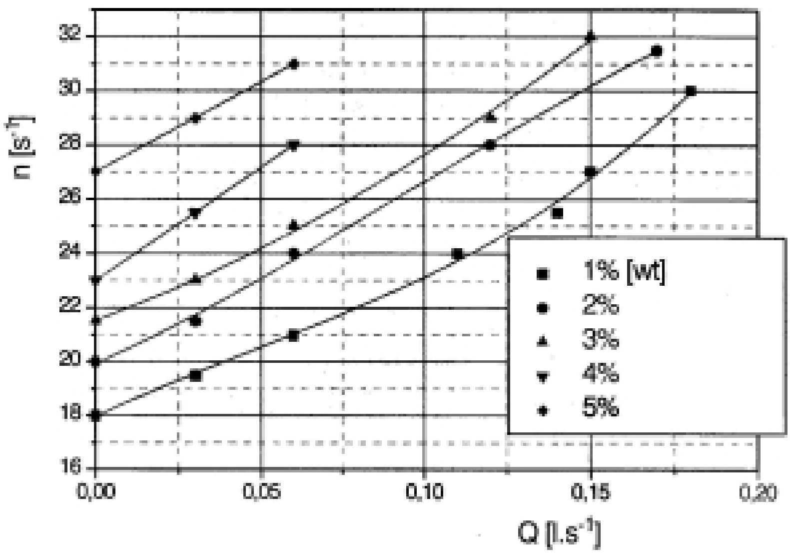

Fig. 11. Complete suspension of the glass spheres (0.3 mm dia.) in the three-phase system

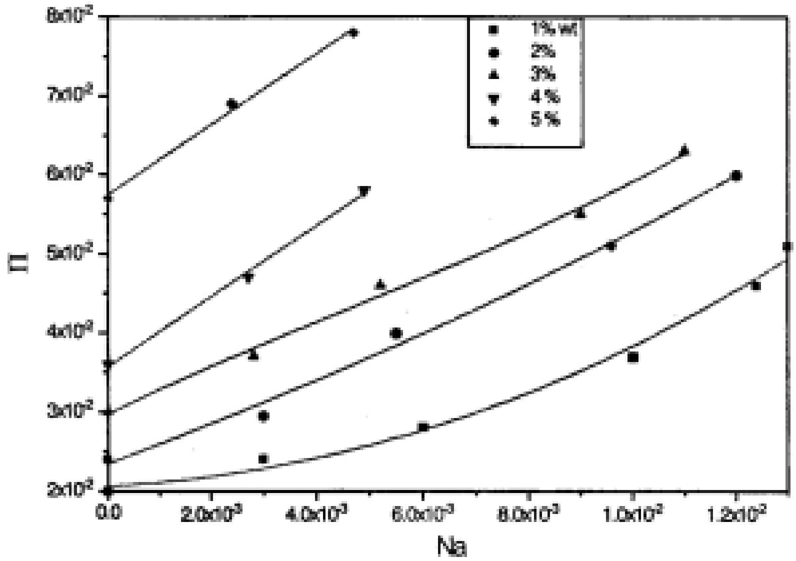

Fig. 12. Complete suspension of the glass spheres in the three-phase system evaluated by Π criterion, spheres dia. 0.3 mm

A new relationship was proposed for the evaluation of the mixing efficiency. Our results have shown that the dependence of the energy consumed to produce the given degree of content homogenization can be very good related to the modified Re number.

The results of tests with the complete suspension of the glass spheres in the water may be expressed by RIEGER's criterion (10). The authors of [12] introduce the following Π values for the Rushton turbine mixer with 6 blades:

$$\Pi = 0.54 \text{ for } H_2/d_m = 1.0,$$
$$\Pi = 0.37 \text{ for } H_2/d_m = 0.67,$$
$$\Pi = 0.35 \text{ for } H_2/d_m = 0.33.$$

Unfortunately in [12] no mention is made about the size, material, shape and concentration of the solid particles.

Tests in the water – air two-phase system pointed out that in the P_g/P vs. Na relationship the revolution frequency can be neglected for $n > 10\ \text{s}^{-1}$ only. For lower n values the suction mixer effect is insufficient and an air ascending component predominates.

The three-phase system was represented by tap water as the continuum, by glass spheres (0.3 mm diameter and concentration from 1 up to 5% wt) as the solid phase and by air (flow rate $0.03 \div 0.18\ \text{dm}^3 \cdot \text{s}^{-1}$) as the gas phase. The higher air flow (Na) values at the given solid concentration cause a higher energy consumption (the necessity of higher n) for the complete suspension of the solid phase. It was possible to express the obtained results by RIEGER's criterion (9) as the function $\Pi = f(Na)$.

Based on the results, a large mixer of this type for 3000 dm^3 vessel was designed and made. The mixer equipment was successfully used to achieve a better clarification of the thick juice in a Slovak sugar factory.

List of symbols

d_m	– mixer diameter	[m]
D	– vessel diameter	[m]
g	– gravity acceleration	[ms^{-2}]
n	– revolution frequency	[s^{-1}]
P_g	– power consumed in aerated system	[W]
P	– power consumed in non-aerated system	[W]
Q	– air flow rate	[m^3s^{-1}]
t_m	– homogenization time	[s]
x_w	– concentration, w/w	[kgkg^{-1},%wt]
μ	– dynamic viscosity	[Pas]
ρ	– liquid density	[kgm^{-3}]
ρ_{mix}	– density of the liquid – solid – gas phase mixture	[kgm^{-3}]

Criteria

$$Eu_m - \mathrm{Po} = \frac{P}{\rho n^3 d_m^5}$$ Euler‘s modified criterion (power number)

$$Na = \frac{Q}{n d_m^3}$$ aeration number

$$\Pi = \frac{P}{\rho_{\mathrm{mix}}}\sqrt{\left[\frac{\rho_L}{g(\rho_{\mathrm{mix}} - \rho_L)}\right]^3 \frac{1}{D^7}}$$ Rieger’s criterion

$$\mathrm{Re}_m = \frac{n d_m^2 \rho}{\mu}$$ Reynolds’ modified criterion

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