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THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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Influence of fluid rheological properties on mixing of solid-liquid suspensions

The problem of non-Newtonian properties of a liquid during the suspension generation in agitated system is investigated. The tested agitator was the standard Rushton turbine. The impeller speed required for particle suspension increased with both the CMC solution concentration, u_{CMC}, and solid/liquid mass ratio in a suspension, U_s. Addition of the sodium chloride to CMC solution caused the decrease of the impeller speed required for suspension as well as stabilised both the CMC solution and the suspension properties.

Nomenclature

D – vessel diameter,
d – impeller diameter,
d_p – particle diameter,
$d_{p,r}$ – reduced particle diameter, d_p/δ_e
g – acceleration due to gravity,
H – liquid height,
h – impeller clearance above the vessel bottom,
K – consistenmcy index of shear thinning,
K' – technical consistency index of shear thinning fluid,
n – flow behaviour index,
n_o – critical impeller speed.

U_s – solid mass ratio to liquid in a suspension,
u_s – solid mass fraction in a suspension,
δ_e – equivalent linear dimension, $(\eta^2/g\rho_l^2)^{1/3}$
η – dynamic viscosity coefficient,
ν – kinematic viscosity coefficient,
ρ – density,
Ar – Archimedes number, $d_{p,r}^3\Gamma_\rho$
Ga – Galileo number, $d_{p,r}^3$
Re_o – Reynolds number, $n_o d^2 \rho_l/\eta$
Γ_ρ – density factor, $\Delta\rho/\rho_l = (\rho_s - \rho_l)/\rho_l$

Subscripts

e – equivalent value,
l – liquid,
p – solid particle,
r – reduced value,
s – solid state,
w – water,
CMC – carboxymethylcellulose sodium salt,
NaCl – sodium chloride.

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1. Introduction

Fluid mixing is of primary importance in many production systems in chemical and process industries, and solid suspending is probably the most common mixing operation. The stirrer applied has to prevent the particles from settling at the bottom of the vessel [14]. The main objectives of agitation in solid-liquid systems can be classified into two categories: uniform suspension of solid particles in liquid and reduction of diffusion resistance around solid particles. The uniform suspension of solid particles is not easily attained, and also is not always required. A very important issue in designing of mixing apparatuses is the state of full particle suspension, at which no particle remains in contact with the vessel bottom for longer than a certain period of time, e.g. 1 s. Considerable attention has been paid to determination of the critical impeller speed required to reach this state. The majority of published papers are based on the results of model experiments for the solid – Newtonian liquid systems, where the effect of single parameters on the critical impeller speed was determined. The paper [15] contains the critical review of existing theories and experimental methods used to determine the critical speed required to lift particles from the vessel bottom. The Newtonian suspension theories can be divided into seven groups:

1. based on the balance between the energy dissipated by the settling particles and the energy dissipated in the fluid by the agitator [7, 10];
2. based on the presumption that the energy needed to suspend the particle from the bottom is proportional to that of turbulent vortices [1];
3. based on a balance between the upward fluid velocity and the particle settling velocity [16-18];
4. concerning the balance between the force of a fluid affecting the particles and the gravity force reduced by buoyancy (for fine particles, $\mathrm{Ar} < 40$) [12];
5. based on the presumption that the agitator must overcome the pressure difference caused by the differences in particle concentrations in upward and downward flows (for large particles, $\mathrm{Ar} > 40$) [13, 19];
6. concerning the balance between the potential energy necessary to achieve suspension and the kinetic energy of fluid flow being discharged from the agitator [17];
7. based on the assumption of proportionality of kinetic energy of turbulent eddies and potential energy gained by the particles – suspension rise is due to turbulent eddies whose sizes are comparable with particle diameters and energy transferred to the particles from these eddies lifting them off the base [5].

It should be emphasized that in several papers the theoretical results are described in dimensionless forms. For example the final process equation resulted from the solution of a problem in [5] is presented as follows:

$$\mathrm{Re}_o = Cu_s^c \left(\frac{d_p}{d}\right)^{1/6} \left(\frac{\Delta\rho}{\rho_l}\right)^{1/2} \mathrm{Ar}^{1/2} \frac{D}{d}. \tag{1}$$

Experimental methods for determination of suspension speed can be divided into two groups: direct and indirect measurements. The direct methods are visual, contactual, radiative and based on observing the interface between sediment and transparent liquid [15]. The direct visual method for determination of the critical impeller speed was firstly used by Zwietering [21]. The method is based on the continuous measuring of the relationship between the height or radius of the non-suspended particle layer and the agitator speed. This method is recommended as giving the most correct results in transparent tanks. Otherwise, other direct methods are useful in industrial vessels, where visual methods cannot be applied [15]. There are various types of solid – Newtonian liquid suspension forming, which are reviewed in [2-4]. The analysis of the literature data directed to the generalized correlation equation has been carried out too. As a result the following dimensionless relationship:

$$\mathrm{Re}_o = C \frac{U_s^a}{(1+U_s)^b \Gamma_\rho^c} \mathrm{Fr}^e \left(\frac{r_s}{1-r_s}\right)^f \left(\frac{d_p}{d}\right)^g \left(\frac{d}{\delta_e}\right)^i \left(\frac{h}{d}\right)^j \left(\frac{D}{d}\right)^k \left(\frac{\rho_s}{\rho_l}\right)^l \left(\frac{w_o}{\omega_e}\right)^m \left(\frac{V_s'}{V_s}\right)^n \tag{2}$$

has been obtained. In most publications the experimental data were elaborated in the following form:

$$\mathrm{Re}_o = f\left(U_s, \Gamma_\rho, \frac{d_p}{d}, \frac{d}{\delta_e}, \frac{D}{d}\right) \tag{3}$$

The other moduli which appear in the analyzed studies, have only been used occasionally. In the majority of previous studies the rheological properties of a fluid have been taken into account only in the Reynolds number formula:

$$\mathrm{Re}_o = \frac{n_o d^2 \rho_l}{\eta} \tag{4}$$

and in an equivalent linear dimension δ_e

$$\delta_e = \left(\frac{\eta^2}{g\rho_l^2}\right)^{1/3} \quad [\mathrm{m}] \tag{5}$$

Studies [2] were carried out in wide ranges of process parameters: $U_s \in (0.010; 0.250)$ [kg s/kg l], $\Gamma_\rho \frac{d_p}{\delta_e} \in (0.996; 18.73)$, $\eta \in (0.00105; 0.0565)$ [Pa · s], $\rho_l \in (998; 1286)$ [kg/m^3]. The Rushton turbines were tested with the diameters $d = 0.050$; 0.075; 0.1125 and 0.150 m in the vessels of diameters D which satisfied the requirements of geometry factors $D/d = 2$; 3 and $h/d = 2/3$; 1; 3/2. The following experimental

relationships with account of the scale-up, have been obtained:
- for $D/d=3$

$$\mathrm{Re}_o = 11356 U_s^{0.176\frac{h}{d}-0.029} \left(\Gamma_\rho \frac{d_p}{\delta_e}\right)^{0.35} \left(\frac{\nu}{\nu_w}\right)^{-0.92} \left(\frac{h}{d}\right)^{1.45} \left(\frac{D^2}{d_1 D_1}\right)^{0.48} \cdot \quad (6)$$

- for D/d = 2

$$\mathrm{Re}_o = 29000 U_s^{0.176\frac{h}{d}-0.029} \left(\Gamma_\rho \frac{d_p}{\delta_e}\right)^{0.35} \left(\frac{\nu}{\nu_w}\right)^{-0.92} \frac{h}{d} \exp\left[0.0111 \left(\frac{D^2}{d_1 D_1}\right)^2\right] \quad (7)$$

where: $d_1 = 0.050$ m; $D_1 = 0.150$ m.

The comparison of the viscosity effect on a critical value of Reynolds number (for $D/d = 3$) from various exemplary studies performed for standard Rushton turbine shows the evident quantitative divergences (Fig. 1). The critical values decreased with the increase of fluid viscosity.

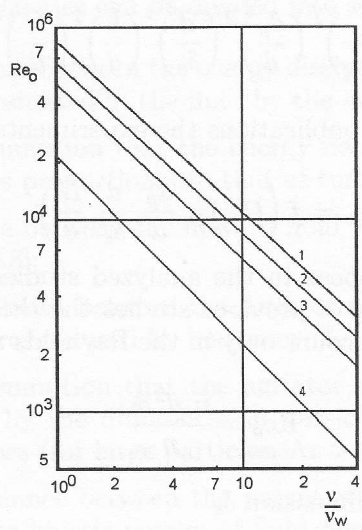

Fig. 1. Effect of the viscosity on critical value of Reynolds number resulting from literature data: 1 – Zwietering [21]; 2 – Hobler, Zabłocki [8]; 3 – Borowski [2]; 4 – Kneule [9].

A number of fluids, in common industrial use, show highly non-Newtonian behaviour. In biotechnological processes liquids have pronounced even visco-elastic properties [20]. In available literature the studies on the fundamental nature of the factors which affect the performance of agitation equipment for the suspension of solid particles in non-Newtonian liquids have not yet been found. The purpose of this study is to determine the suspension speed for liquids obeying the power-law.

2. Experimental procedure

Measurements were carried out in a flat-bottom plexi-glass vessel with inside diameter of $D = 0.225$ m with four baffles of the width $b = 0.1D$. The tested agitator was a standard Rushton turbine of diameter $d = 0.075$ m with six blades. The impeller was placed centrically in the axis of the tank. The ratio of the vessel diameter to agitator diameter was $D/d = 3$ and ratios of h/d were equal to 1 and 3/2. By employing the MIN-2 control system both, the smooth change of impeller rotation and its stability, have been obtained. The real rotation speed was determined by the use of the system equipped with the disk with a port placed on the agitator shaft and with the photo-electric cell which transferred the impulse to the automatic frequency meter PFL-2. Process temperature was fixed at $T = 293 \pm 0.5$ K.

The solid phase was made up of high-silica sand particles with the density of $\rho_s = 2549$ [kg/m^3] and mean diameter of $d_p = 0.008 - 0.0010$ m. The Newtonian liquid was water with viscosity $\eta = 10^{-3}$ [P · s] and density $\rho_l = 998$ [kg/m^3]. The non-Newtonian fluids were aqueous CMC solutions and the CMC solutions with sodium chloride (NaCl) additives of various concentrations. The concentration of CMC in water was equal to $u_{\mathrm{CMC}} \in (0.003; 0.015)$ [kg CMC/kg]. The high-molecular CMC aqueous solutions as Tomsian fluids can undergo a mechanical degradation. The sodium chloride added to the solution stabilizes its rheological properties. In the experiments the mass ratio of particles to liquid were equal to $U_{\mathrm{NaCl}} = 0.010; 0.041; 0.076; 0.120$ and 0.150 [kg NaCl/kg l]. In the present report the effect of sodium chloride on critical speed was studied for the CMC/water solution of concentration of $u_{\mathrm{CMC}} = 0.006$ [kg CMC/kg].

The measurements of rheological characteristics of studied non-Newtonian liquids in Rheotest RV2 in the range of shear velocities $\gamma \in (300; 1500)$ [s^{-1}] have been carried out. As a result of the analysis there emerged the possibility of the description of the flow curves in a form of two-parameters equations in given limited ranges of shear velocity:

$$\tau = K\gamma^n; \quad \tau_w = K'\gamma_w^{n'} = K\left(\frac{3n+1}{4n}\right)^n \gamma_w^n. \tag{8}$$

Additionally, the effect of NaCl concentration on consistency index has been evaluated (Fig. 2).

The preliminary measurements performed in water (Fig. 3) showed that the critical agitator speed obtained for $h/d = 1$ is lower than that for $h/d = 3/2$. This regularity has been observed for all studied systems. Thus the experimental data in a majority of the study for $h/d = 1$ have been analyzed. The results of this study are comparable to the literature data (Fig. 4). The function of the impeller speed required for the particle suspension depending on the CMC solution concentration, u_{CMC}, and solid mass ratio to liquid in a suspension U_s (Fig. 5) showed that the critical value of n_o increases with both concentrations. The exemplary relationships $n_o = f(U_s, u_{\mathrm{NaCl}})$ are presented in Fig. 6.

Addition of the sodium chloride to CMC solution causes the decrease of the

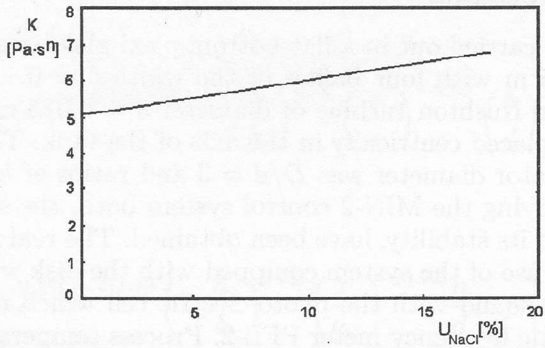

Fig. 2. Sodium chloride concentration effect on the consistency index for CMC solution with $u_{CMC} = 0.006$ [kg CMC/kg].

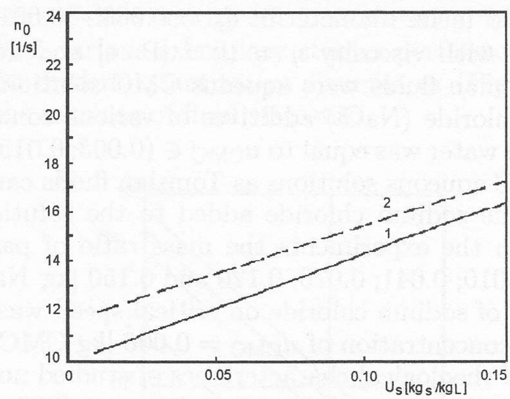

Fig. 3. Effect of the impeller clearance above the vessel bottom on critical speed for water-sand: 1 – $h/d = 1$; 2 – $h/d =$

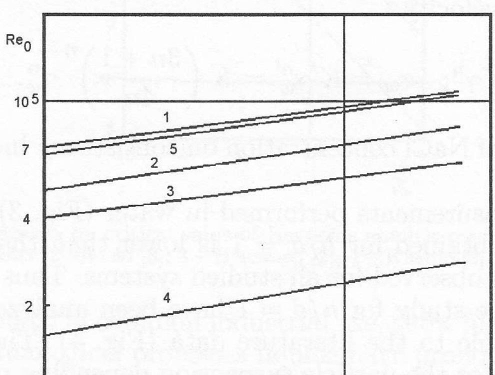

Fig. 4. Comparison of the results for standard Rushton turbine with the literature data (system water/sand): 1 – Zwietering [21]; 2 – Hobler, Zablocki [8]; 3 – Borowski [2]; 4 – Kneule [9]; 5 – own results.

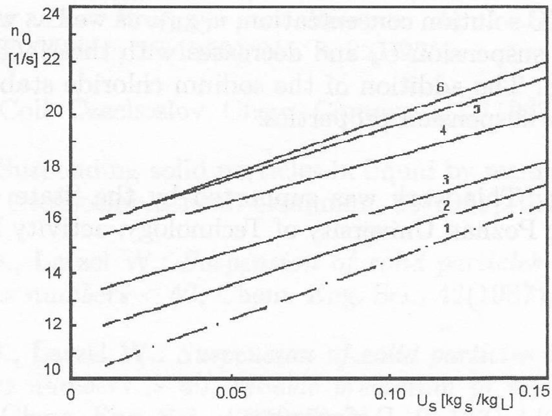

Fig. 5. Effect of concentration of CMC aqueous solutions on critical agitator speed: 1 – water; 2 – $u_{CMC} = 0.003$; 3 – $u_{CMC} = 0.006$; 4 – $u_{CMC} = 0.009$; 5 – $u_{CMC} = 0.012$; 6 – $u_{CMC} = 0.015$.

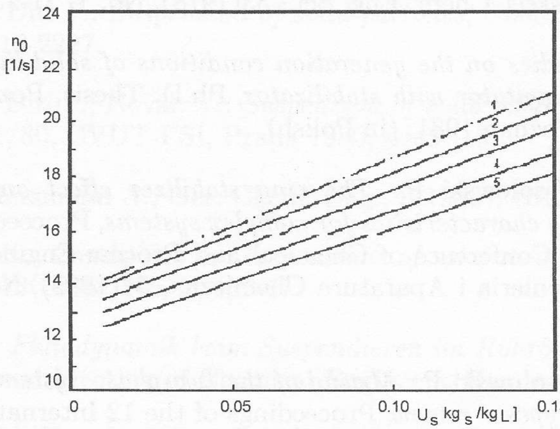

Fig. 6. Effect of concentration of NaCl on critical agitator speed for CMC/water solution of mass fraction $u_{CMC} = 0.006$ [kg CMC/kg]: 1 – $u_{NaCl} = 0$; 2 – $u_{NaCl} = 0.03$; 3 – $u_{NaCl} = 0.06$; 4 – $u_{NaCl} = 0.15$; 5 – $u_{NaCl} = 0.18$ [kg NaCl/kg].

impeller speed required for suspension. This phenomenon can be explained by the electrolytic effect on the apparent viscosity values in aqueous solutions. Additionaly, the following phenomena have been observed: holding in suspension in CMC solutions is easier than in clear water, departure of the particles from the vessel bottom was more difficult because the settling velocity of the particles increases with the increase of shear-thinning properties of a liquid, addition of the sodium chloride stabilized both the CMC solution and the suspension properties.

3. Conclusions

It has been shown that the critical agitator speed obtained for $h/d = 1$ is lower than that for $h/d = 3/2$. The impeller speed required for particle suspension increases with the CMC solution concentration, u_{CMC}, as well as with the solid to liquid mass ratio in a suspension U_s and decreases with the NaCl concentration in shear-thinning fluid. The addition of the sodium chloride stabilized both the CMC solution and the suspension properties.

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Wpływ własności reologicznych płynu na mieszanie zawiesiny ciała stałego w cieczy

Streszczenie

W pracy opisano badania wpływu nienewtonowskich własności cieczy na wytwarzanie zawiesiny w mieszalniku. Podstawowym elementem było mieszadło standardowe turbinowe Rushtona. Wykazano, że krytyczna wartość liczby obrotów mieszadła jest mniejsza dla stosunku wysokości zawieszenia mieszadła do jego średnicy $h/d = 1$ niż dla $h/d = 3/2$.

Prędkość obrotowa niezbędna do wytworzenia zawiesiny rosła zarówno ze stężeniem CMC w roztworze, jak i stosunkiem masowym ciała stałego w układzie. Dodatek soli sodowej do roztworu CMC powodował obniżenie wartości liczby obrotów mieszadła, niezbędnej do wytworzenia zawiesiny i jednocześnie stabilizował zarówno nienewtonowskie własności roztworu CMC, jak i własności samej zawiesiny.