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EFFECT OF IMPELLER SHAPE ON SOLID PARTICLE SUSPENSION

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This paper deals with the effect of impeller shape on off-bottom particle suspension. On the basis of numerous suspension measurements, correlations are proposed for calculating the just-suspended impeller speed for a standard pitched four-blade turbine and three types of hydrofoil impellers produced by TECHMIX for several particle sizes and for a wide range of particle concentrations. The suspension efficiency of the tested impellers is compared with the efficiency of a standard pitched blade turbine on the basis of the power consumption required for off-bottom suspension of solid particles. It is shown that the standard pitched blade turbine needs highest power consumption, i.e. it exhibits less efficiency for particle suspension than hydrofoil impellers produced by TECHMIX.

Keywords: mixing, axial impeller, hydrofoil impeller, just-suspended impeller speed, electrochemical method

1. INTRODUCTION

Mixing suspensions is a very important process operation. Suspensions are frequently mixed when they are prepared or homogenised, and in mass transfer operations between solid particles and a liquid. In mass transfer operations (e.g. dissolution, crystallisation and precipitation), the key process objective usually is to make all the surface area of the solids available for mass transfer. It is attained at complete off-bottom suspension. The just suspended impeller speed providing complete off-bottom suspension satisfies this objective. The following Zwietering's (1958) empirical correlation is often recommended for just suspended speed calculation

$$n = S\left(\frac{g\Delta\rho}{\rho}\right)^{0.45} \frac{X^{0.13} d_p^{0.2} \upsilon^{0.1}}{d^{0.85}} \tag{1}$$

where S is constant dependent on mixing equipment geometry.

A number of papers were published on particle suspension in agitated vessels. A review of the literature was presented by Rieger and Ditl (1994), and more recently by Kassat and Pandit (2005). Ditl and Rieger (2006) presented a review of recommendations for the design of mixing equipment for suspensions, but they were based only on visual observations of off-bottom suspension with two volumetric particle concentrations, 2.5% and 10%. The authors concluded that axial flow impellers are the most suitable agitators in these cases. A recent paper by Jirout and Rieger (2011) extended impeller-design recommendations for particle suspension for many axial-flow impeller types in a wide range of particle sizes and volumetric particle concentrations, mostly up to 15%. The aim of this paper

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was to extend Jirout and Rieger's (2011) information to a standard pitched four-blade turbine and three types of hydrofoil impellers produced by TECHMIX for a wide range of volumetric particle concentrations up to 40%.

2. THEORETICAL BACKGROUND

The following equation was recommended for evaluating just suspended impeller speed *n* on the basis of inspection analysis of basic equations by Rieger and Ditl (1994) for a given particle content and agitator type in the turbulent region in

$$Fr' = \frac{n^2 d\rho}{g\Delta\rho} = f\left(\frac{d_p}{D}\right) \tag{2}$$

For relatively small particles, (less than approximately 0.005 *D*) the dependence between the modified Froude number and a dimensionless particle size can be formulated in the power form

$$Fr' = C\left(\frac{d_p}{D}\right)^{\gamma} \tag{3}$$

The values of coefficients C and γ depend on particle volumetric concentration c. The following empirical equations were proposed by Rieger (2000) to describe these dependencies

$$C = A\exp(Bc) \tag{4}$$

$$\gamma = \alpha + \beta c \tag{5}$$

The dimensionless criterion

$$\pi_s = Po\sqrt{Fr'^3 (d/D)^7} \tag{6}$$

was proposed by Rieger (1993) for comparing the agitator power consumption necessary for suspension of solid particles. The results of power consumption measurements in the turbulent regime are presented in the form of power number *Po*

$$Po = \frac{P}{\rho n^3 d^5} \tag{7}$$

3. EXPERIMENTAL

A standard pitched four-blade turbine and three types of hydrofoil impellers produced by TECHMIX (TX335-profiled blade impeller of high solidity, TX445- trapezoidal folded blade impeller and TX535- modified propeller), see Fig.1, were used in the model measurements. The ratio of the vessel to the agitator diameter *D/d* was 3. Flow characteristics of these impellers were tested by Fořt et al. (2010). The height of the impeller above the vessel bottom was chosen near optimum from the point of view of operating conditions and power consumption for particle suspension (see e.g. Ceres et al., 2008). The height of the pitched four-blade turbine was equal to 0.5 *d*; the height of the TECHMIX impellers above the vessel bottom was equal to 0.75 *d*. The impellers were operated to pump the liquid down towards the bottom of the vessel. The measurements were carried out in a dish-bottomed vessel 300 mm in diameter. The vessel was equipped with four radial baffles of width $b = 0.1 \cdot D$. The height of the liquid level was equal to the vessel diameter $H = D$.

Suspensions of glass particles in 2.5% NaCl water solutions were used in the suspension measurements. The diameters of the glass ballotine particles varied in the range from 0.18 mm to 0.9 mm, and their volumetric concentration varied in the range from 0.025 to 0.4. The just-suspension impeller speeds were measured by an electrochemical method described e.g. in Jirout et al. (2005) and checked visually. No significant differences between electrochemical and visual measurements were observed as shown in Fig.2. However visual measurement needs an experienced experimenter especially in concentrated suspensions of greater particles.

Fig. 1. Tested impellers: a) Pitched four-blade turbine (PBT), b) Techmix TX 335, c) Techmix TX445, d) Techmix TX535

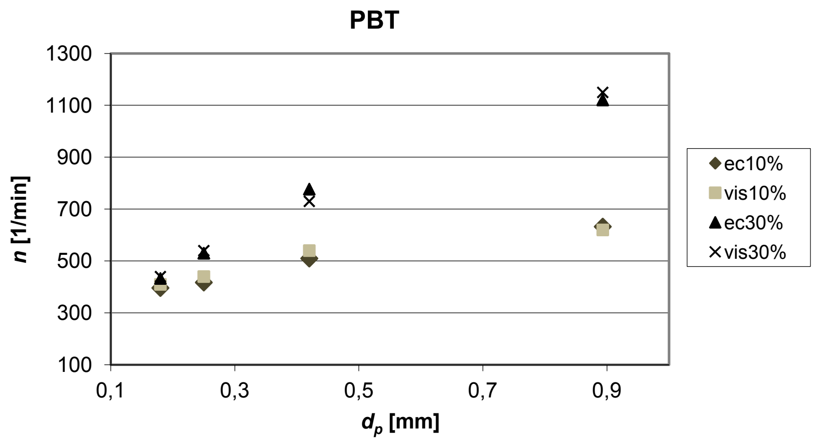

Fig. 2. Comparison of just suspended pitch blade turbine speed dependence on particle diameter for selected particle concentration 10 and 30% measured by electrochemical and visual methods

In electrochemical measurements, the dependence of the arithmetic mean value and the standard deviation of the probe electric current on the impeller speed was suggested for observation. A typical dependence of these parameters on the measurement is shown in Fig. 3. In a suspension measurement, there are three different states of suspension that appear as the impeller speed increases. First, a particle layer is settled on the bottom of the vessel (Fig. 3 – A). As the impeller speed increases, the particle layer becomes thinner, and particles are alternately suspended and settled on the bottom of the vessel (Fig. 3 – B). After reaching just-suspended impeller speed, all particles are suspended and no particle remains on the bottom of the vessel (Fig. 3 – C). These three suspension states can be resolved by an electrochemical method.

The just-suspended impeller speed can be determined from the dependencies of the arithmetic mean value and the standard deviation of the probe electric current on the impeller speed, as shown in Fig. 3. The just off-bottom particle suspension state is represented by the increase in the arithmetic mean value and the standard deviation of the current. The just-suspended impeller speed can be determined by a rapid increase in both of these parameters. To completely remove the influence of the experimenter on the observed critical impeller speed, all the data records are handled by computer programs, including determining the just-suspended impeller speed.

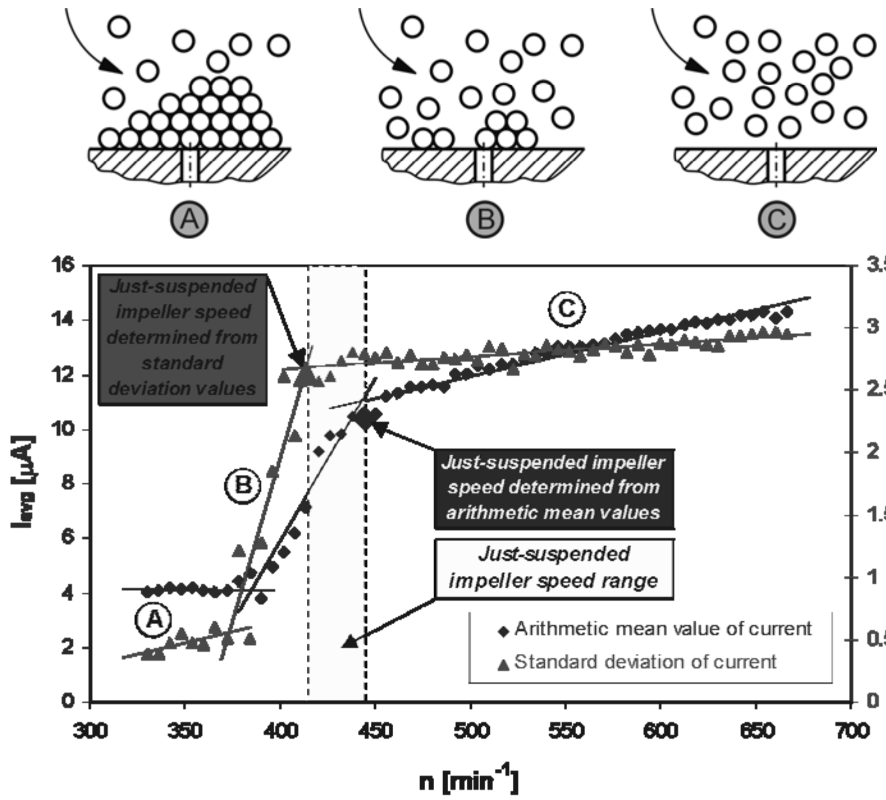

Fig. 3. Typical dependence of the arithmetic mean value and the standard deviation of the probe electric current on impeller speed

Flush probes mounted at the vessel bottom were used in our measurements. Vessel bottom was equipped with six ED probes (Fig. 4). Probes were fabricated of platinum wire with a diameter of 0.5 mm. One baffle was used as a counter electrode. An electrochemical interface connected with a PC secured on-line measurement of the current of six electrodes at a time. Only three electrodes located in critical places from the viewpoint of identifying just off-bottom suspension state were used. These were probes number 1, 7 and 8.

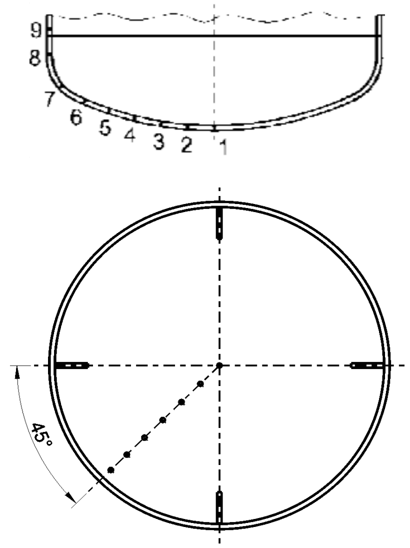

Fig. 4. Position of ED probes on vessel bottom

The accuracy of the method for determining just-suspended impeller speed was evaluated from several repeated measurements. Just-suspended impeller speed was determined with accuracy 3 %.

A turntable with tensometric pick-up of the torque was used in the power consumption measurements. The power measurements were carried out with a water and glycerol solution.

4. EXPERIMENTAL RESULTS

The primary suspension experimental data was transformed into dimensionless criteria and plotted as suspension characteristics. The suspension characteristics for the turbulent region are the dependencies of modified Froude number Fr' on the dimensionless particle size d_p/D at a constant volumetric particle concentration c. These dependencies for selected concentrations and impeller TX535 are depicted in Fig.5. This figure shows that the speeds necessary for particle suspension (also Fr') increase with increasing particle size and concentration.

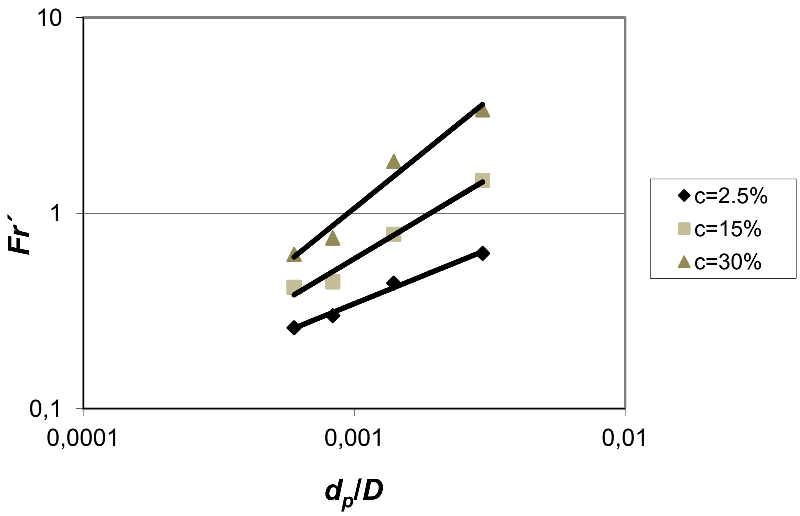

Fig. 5. Example of suspension characteristics Eq. (2) for selected volumetric particle concentration c – impeller TX535

The regression of the suspension characteristics was evaluated in the power form according to Eq. (3). The plots of exponents γ and coefficients C on particle volumetric concentration c are shown in Figs. 6-13. These figures show that γ rises linearly with increasing c. The dependences of coefficients C on particle concentration c show that the dependences can be approximated in semi-logarithmic coordinates by straight lines. This is in agreement with Eqs. (4) and (5). The constants in Eqs.(4) and (5) for all impellers used in the experiments are summarised in Table 1.

Table 1. Values of constants in Equations (5) and (6)

Impeller	A	B	α	β
PBT	2.47	23.2	0.301	2.95
TX335	5.97	19.4	0.444	2.41
TX445	7.64	18.7	0.474	2.25
TX535	17.0	16.7	0.562	1.90

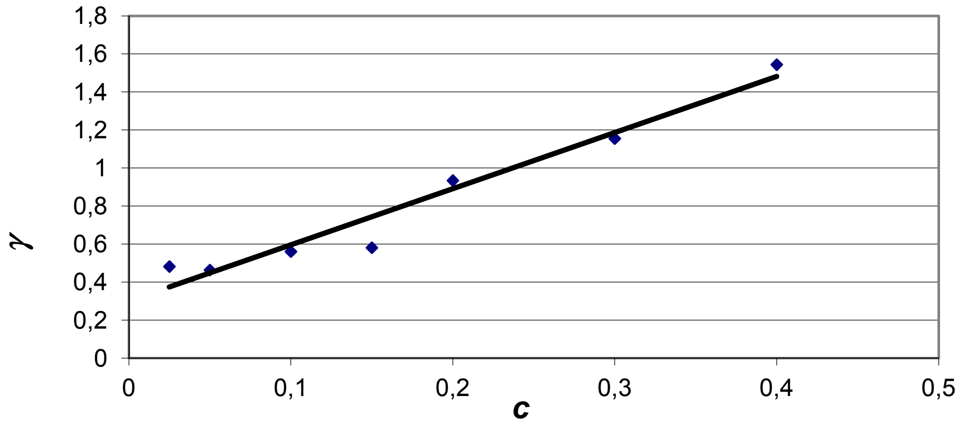

Fig. 6. Dependence of coefficient γ from Eqs. (3) and (5) on volumetric particle concentration c – pitched four blade turbine

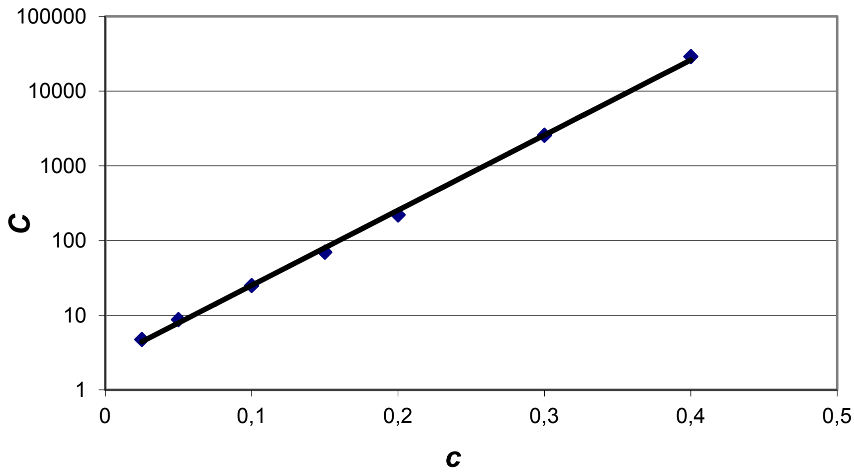

Fig. 7. Dependence of coefficient C from Eqs. (3) and (4) on volumetric particle concentration c - pitched four blade turbine

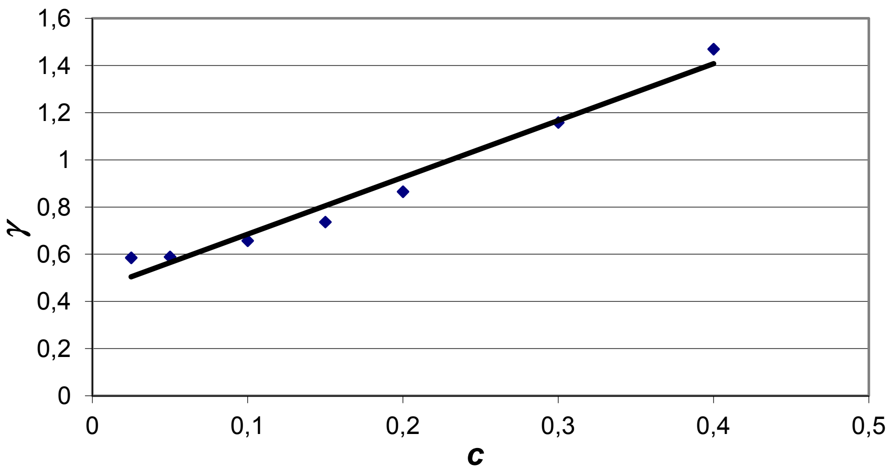

Fig. 8. Dependence of coefficient γ from Eqs. (3) and (5) on volumetric particle concentration c – TX 335 impeller

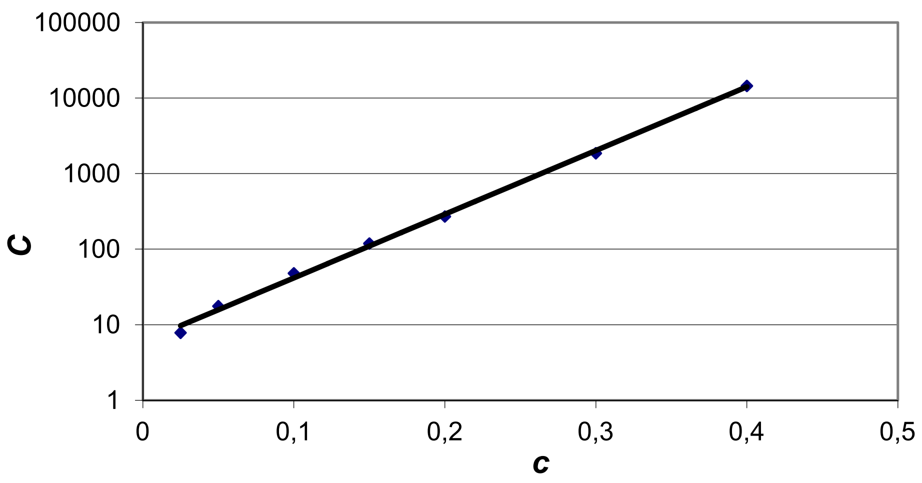

Fig. 9. Dependence of coefficient *C* from Eqs. (3) and (4) on volumetric particle concentration *c* - TX 335 impeller

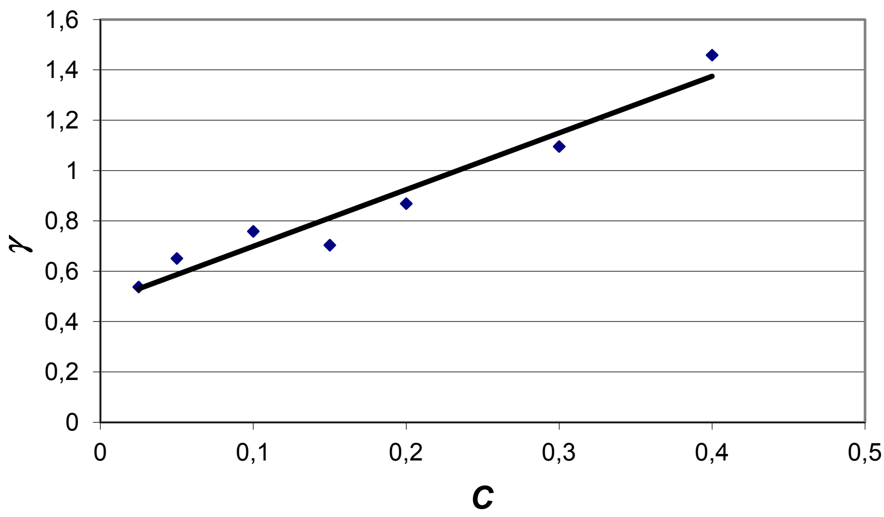

Fig. 10. Dependence of coefficient γ from Eqs. (3) and (5) on volumetric particle concentration *c* – TX 445 impeller

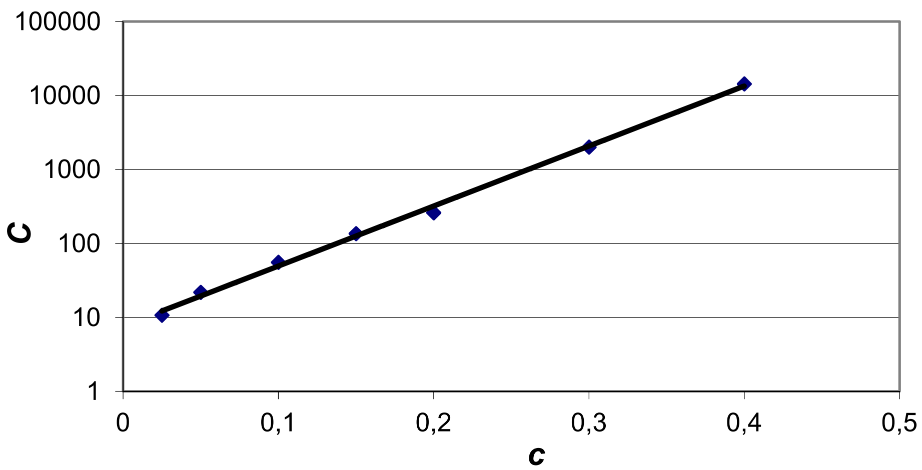

Fig. 11. Dependence of coefficient *C* from Eqs. (3) and (4) on volumetric particle concentration *c* - TX 445 impeller

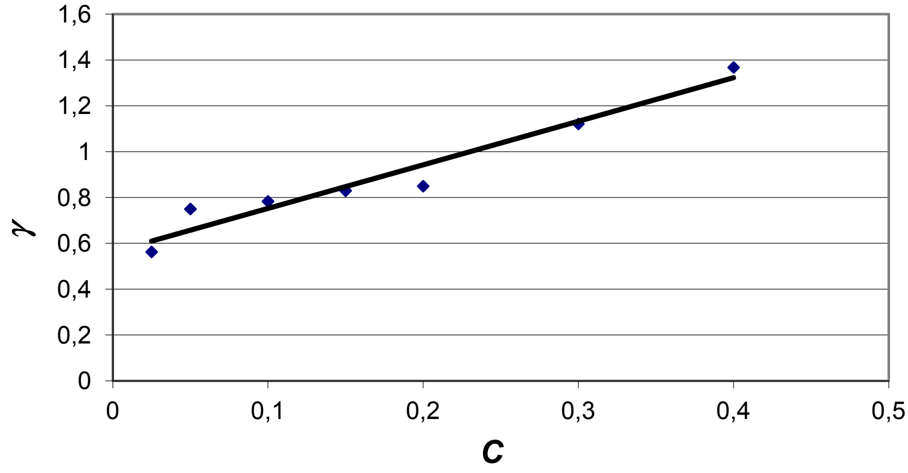

Fig. 12. Dependence of coefficient γ from Eqs. (3) and (5) on volumetric particle concentration c – impeller TX535

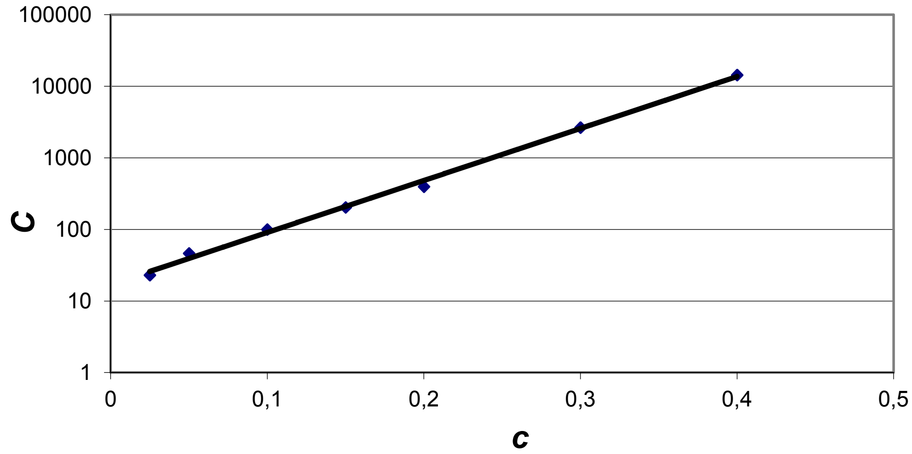

Fig. 13. Dependence of coefficient C from Eqs. (3) and (4) on volumetric particle concentration c – impeller TX535

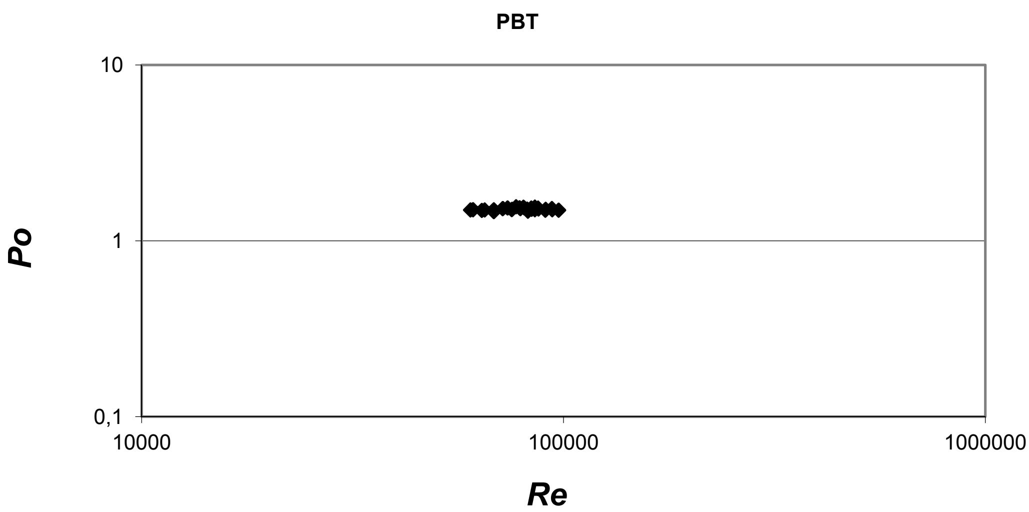

Fig. 14. Dimensionless power characteristic – pitched four-blade turbine

The power curve, i.e. the dependence of the power number on the Reynolds number for the pitched blade turbine carried out by measurements with water is shown in Fig.14. The power curves for TX impellers obtained by measurements with water and glycerol solutions are shown in Figs. 15 – 17. These figures show clearly that the power number in the range of Reynolds number values used in experiments is constant and does not depend significantly on the Reynolds number. The power number values are summarised in Table 2. These values were obtained by measurements with pure liquids but they can be used also for suspensions if density of liquid is replaced by density of suspension, as verified in Ceres (2010).

Table 2. Values of power number Po of tested axial impellers

Impeller	PBT	TX335	TX445	TX535
Po	1.52	0.9	0.9	0.65

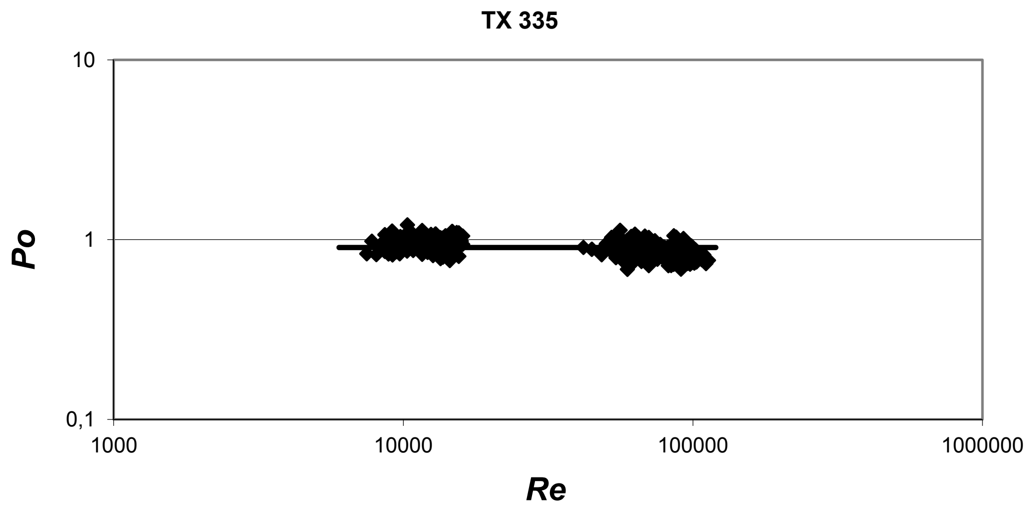

Fig. 15. Dimensionless power characteristic – impeller TX 335

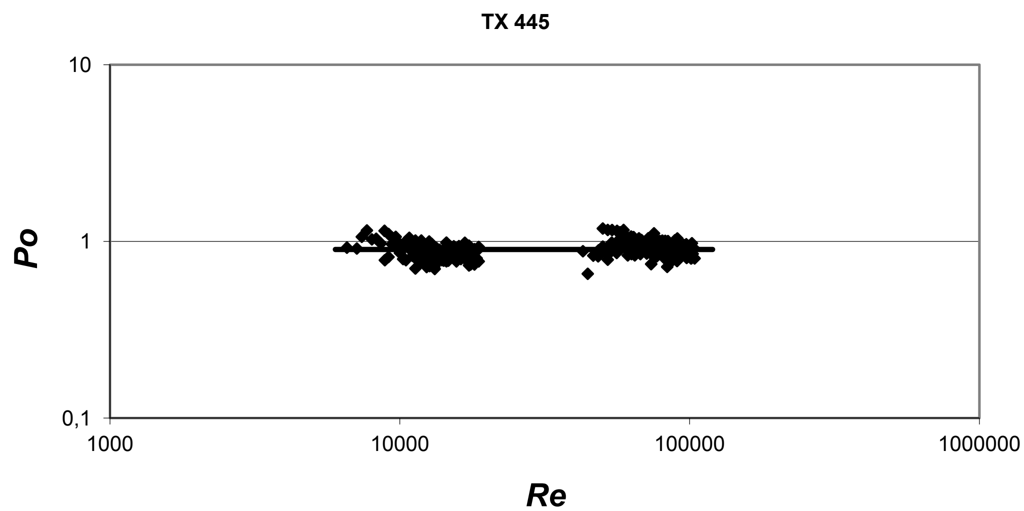

Fig. 16. Dimensionless power characteristic – impeller TX445

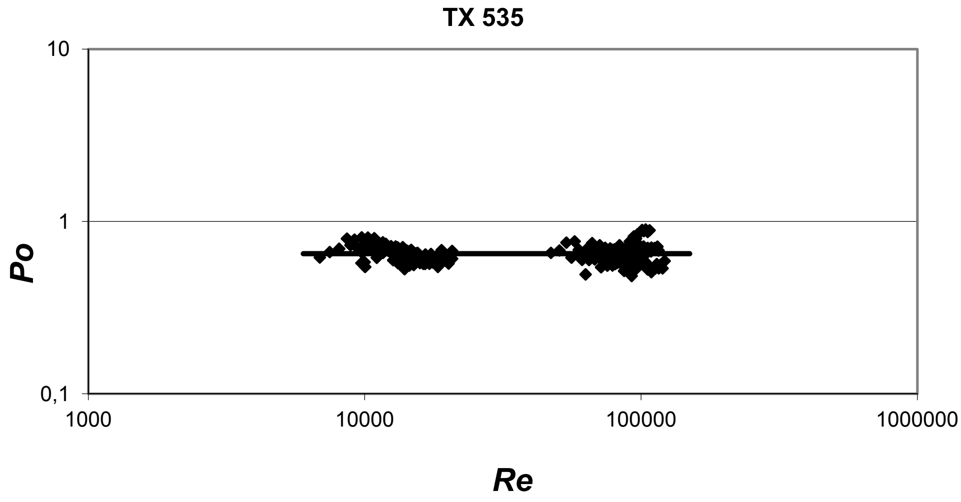

Fig. 17. Dimensionless power characteristic – impeller TX535

5. DISCUSSION

Comparing constant value of exponent above particle diameter d_p presented by Zwietering (Eq.(1)) with our values of variable exponent $\gamma/2$, it is obvious that good agreement is as to be observed at small concentrations only. It is probably caused by the fact that our values of volumetric particle concentration are much higher than Zwietering´s values characterised by relative mass fractions X up to 20%. At small concentrations the differences between our values $\gamma/2$ are not far from Zwietering´s value 0.2. Also exponents above particle concentration are not constant and increase with particle concentration and size as shown in Fig.18 calculated on the basis of Eqs.(3-5). As shown in Rieger and Ditl (1994), no viscosity dependence was observed in turbulence region.

The dependences of the modified Froude number on the relative particle size for several particle contents calculated from Eqs. (3-5) are shown in Figs. 19-21. It follows from these figures that impeller TX535 exhibits the highest modified Froude number (and also the critical agitator speed for suspension) for all particle sizes and concentrations.

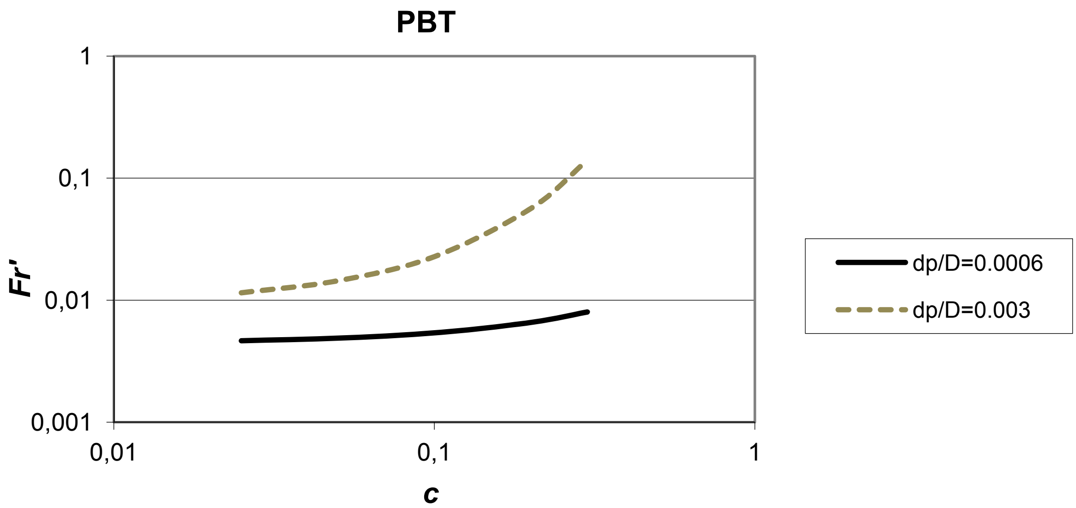

Fig. 18. Dependence of the modified Froude number on particle concentration for selected values of the relative particle size d_p/D calculated from Eqs. (3-5)

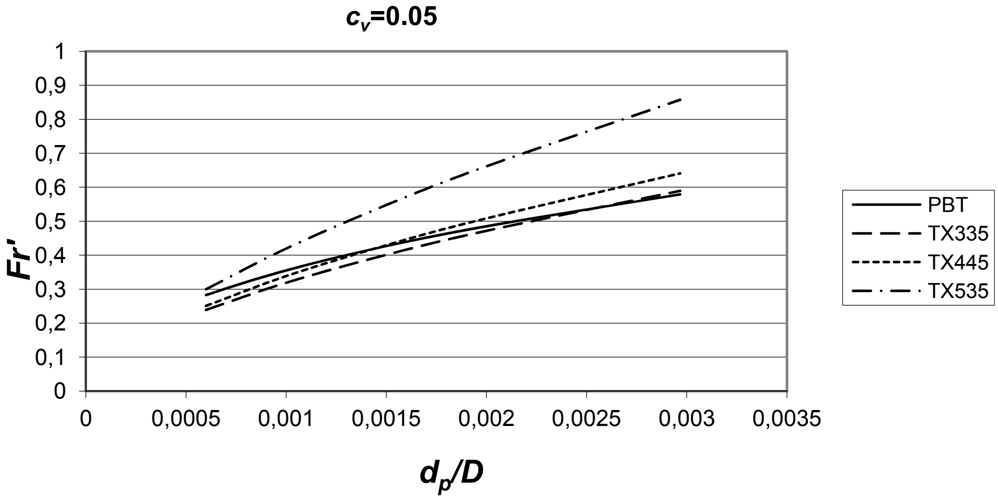

Fig. 19. Dependence of the modified Froude number on the relative particle size d_p/D for particle contents c = 0.05 calculated from Eqs. (3-5)

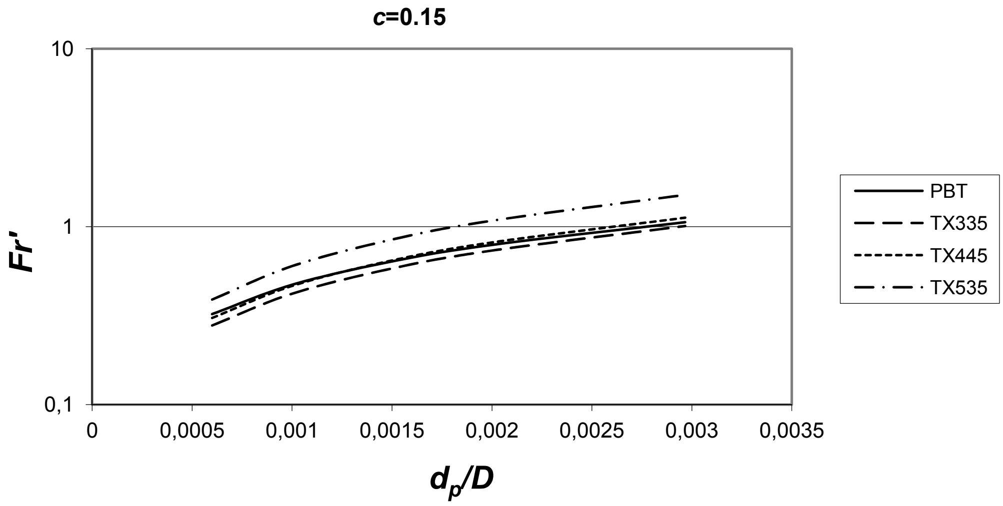

Fig. 20. Dependence of the modified Froude number on the relative particle size d_p/D for particle contents c = 0.15 calculated from Eqs. (3-5)

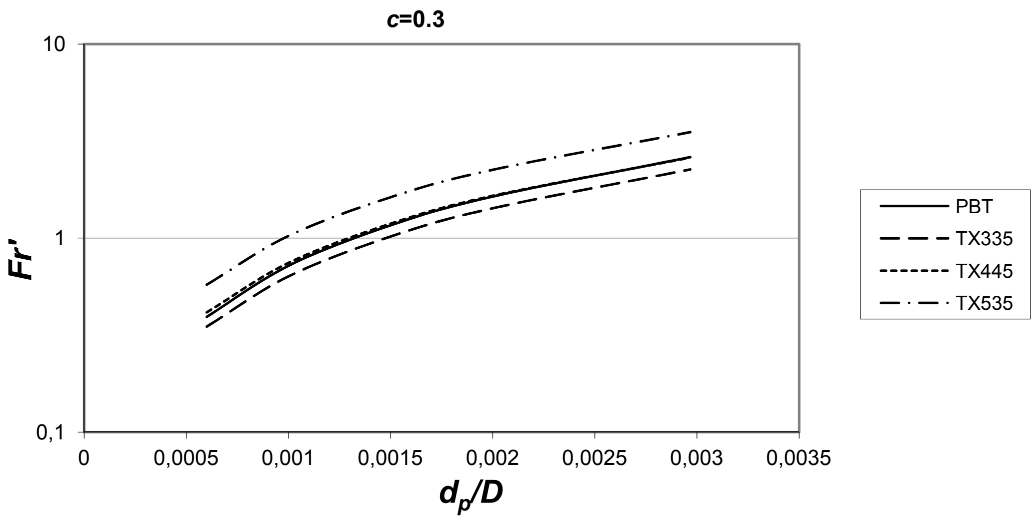

Fig. 21. Dependence of the modified Froude number on the relative particle size d_p/D for particle contents c = 0.3 calculated from Eqs. (3-5)

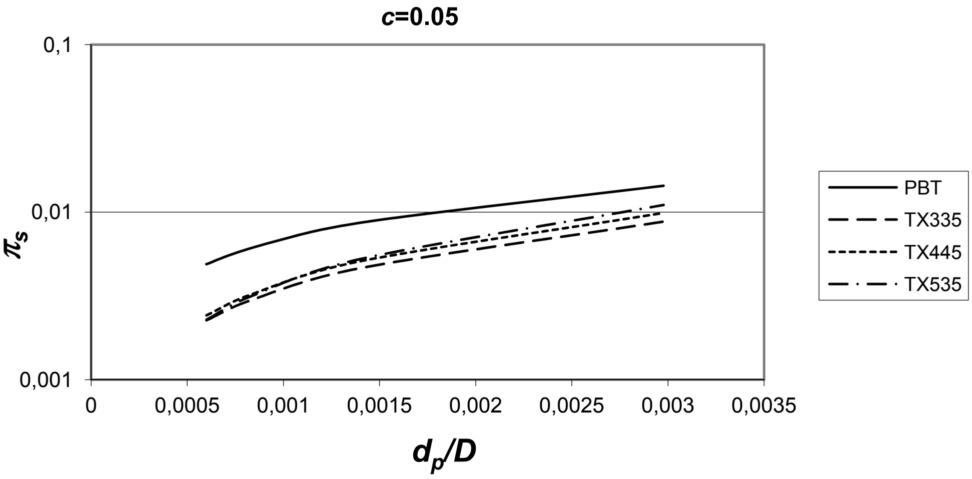

Fig. 22. Dependence of the dimensionless power consumption for off-bottom particle suspension π_s on the relative particle size d_p/D for particle contents c = 0.05 calculated from Eqs. (3-6)

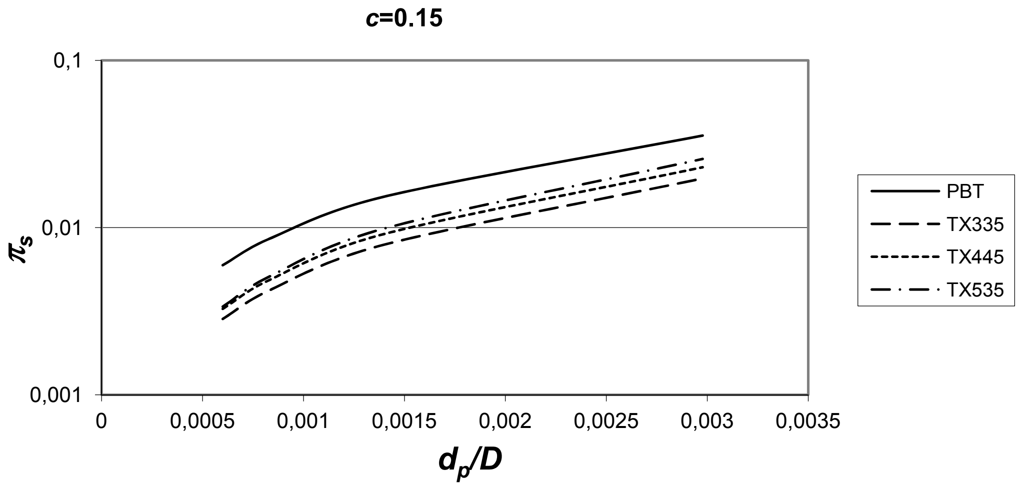

Fig. 23. Dependence of the dimensionless power consumption for off-bottom particle suspension π_s on the relative particle size d_p/D for particle contents c = 0.15 calculated from Eqs. (3-6)

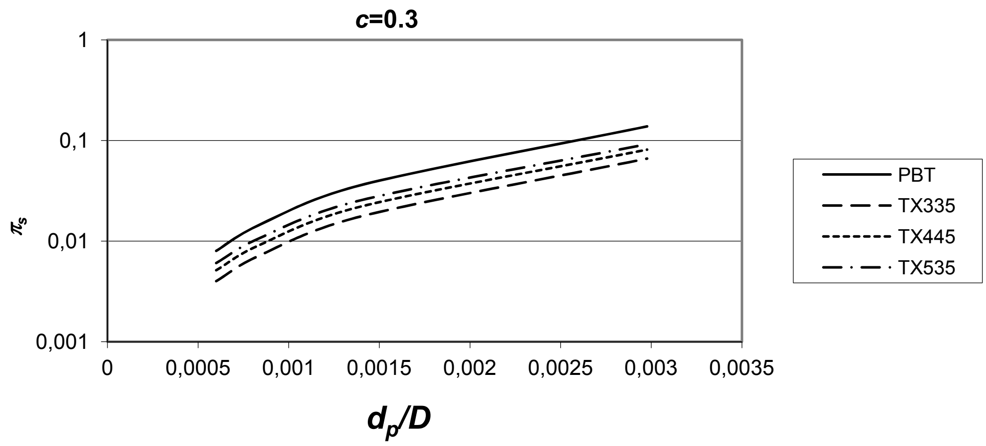

Fig. 24. Dependence of the dimensionless power consumption for off-bottom particle suspension π_s on the relative particle size d_p/D for particle contents c = 0.3 calculated from Eqs. (3-6)

The dependences of the π_s criterion on relative particle size for several particle contents calculated from Eqs. (3-6) are shown in Figs. 22-24. It follows from Figs. 22-24 that the highest power consumption for particle suspension is required by the pitched blade turbine, and lowest power consumption is required by impeller TX335, for most particle sizes and concentrations. It can be caused by the fact that TX 335 impeller exhibits the highest pumping efficiency (see Fořt et al., 2010). By contrast TX 335 is heavier and its production is more expensive and therefore for less concentrated suspensions, where the differences between the individual TX impellers are less significant, the TX 445 and 535 agitators can be recommended.

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SYMBOLS

c	volumetric concentration of particles
d	agitator diameter, m
d_p	particle diameter, m
D	vessel diameter, m
Fr'	modified Froude number, $Fr'=n^2d\rho/g\Delta\rho$
g	gravity acceleration, m s^{-2}
n	agitator speed, s^{-1}
P	power, W
Po	power number, $Po=P/\rho n^3d^5$
Re	Reynolds number, $Re=nd^2/\nu$
X	mass of solid/mass of liquid x 100

Greek symbols

ν	kinematic viscosity, m^2 s^{-1}
ρ	liquid density, kg m^{-3}
$\Delta\rho$	solid-liquid density difference, kg m^{-3}

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