# Impeller design for mixing of suspensions

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***Abstract***

This paper deals with effect of impeller type on off-bottom particle suspension. On the basis of numerous suspension measurements there were proposed correlations for calculation just-suspended impeller speed of eleven impeller types and geometries in the wide range of concentrations and particle diameters. The suspension efficiency of tested impellers was compared by means of the power consumption required for off-bottom suspension of solid particles.

## 1. Introduction

Mixing of suspensions is very important hydraulic operation. It frequently appears at preparation of dispersions, their homogenisation, mass transfer operations between solid particles and liquid that is often accompanied by a chemical or biochemical reaction. It is estimated that about 60 % of mixing is related to the heterogeneous system: particulate solid phase-liquid.

Number of papers on particle suspension in agitated vessels was published. Review of this knowledge was presented by Rieger and Ditl [1] and latterly by Kasat and Pandit [2]. Ditl and Rieger presented in [3] review of recommendation for designing of mixing equipment for suspensions, however, based on measurements with two volumetric particle concentrations 2,5 % and 10 % only. From their conclusions it follows, that it is generally understood that axial-flow pattern impellers are the most suitable agitators in such cases. This article extends impeller-designing recommendations for particle suspension with many axial-flow impellers types in wide range of concentrations and particle diameters. It is written to help designers to choose between alternative impellers and to calculate the critical (just-suspended) impeller speed and power consumption necessary for off-bottom suspension of solid particles.

## 2. Theoretical background

In order to design mixing apparatuses it is important to know the reference state of just off-bottom particle suspension that is often defined as the state at which no particle remains in contact with the vessel bottom for longer than a certain time (e.g. 1 sec). The impeller speed corresponding to this state is referred to as the critical (just-suspended) impeller speed $n_c$.

On the basis of inspection analysis of the equation of continuity, the Navier-Stokes equation and the equation expressing balance of forces affecting the suspended particle Rieger and Ditl [1] proposed the following relationship among the modified Froude number $Fr'$, the dimensionless particle diameter $d_p/D$ and the mean volumetric concentration of solid phase $c_v$

$$Fr' = \frac{n_c^2 d\,\rho}{g\,\Delta\rho} = f\left(\frac{d_p}{D}, c_v\right). \qquad (1)$$

This relation holds for geometrically similar mixing equipment and turbulent regime.

The results of critical (just-suspended) impeller speed measurements for the given solid phase concentration $c_v$ can be correlated in the power form, separately for relatively fine and large particles

$$Fr' = C_i \left( \frac{d_p}{D} \right)^{\gamma_i} \tag{2}$$

with different exponents $\gamma_1$ and $\gamma_2$ and coefficients $C_1$ and $C_2$ for relatively fine and large particles, respectively.

Using superposition principle Rieger [4] substituted the two relationships for relatively fine and large particles with following single correlation for whole range of dimensionless particle diameters $d_p/D$

$$Fr' = \frac{C_1 \left( \frac{d_p}{D} \right)^{\gamma_1}}{\left\{ 1 + \left[ \frac{C_1}{C_2} \left( \frac{d_p}{D} \right)^{\gamma_1 - \gamma_2} \right]^{10} \right\}^{1/10}} \tag{3}$$

The values of coefficients $C_i$ and $\gamma_i$ depend on particle volumetric concentration $c_v$. A mathematical description of these dependencies was proposed by Rieger [5, 6] in the form

$$C_i = A_i \exp(B_i c_v) \tag{4}$$

and

$$\gamma_i = \alpha_i + \beta_i c_v \, . \tag{5}$$

The suspension efficiency of impellers can be compared by means of the dimensionless power consumption necessary for suspension of solid particles. The following dimensionless criterion $\pi_s$ was proposed by Rieger [7] for this purpose

$$\pi_s = \frac{P}{\rho_{su}} \left( \frac{\rho}{g \Delta \rho} \right)^{\frac{3}{2}} \left( \frac{1}{D} \right)^{\frac{7}{2}} = Po \cdot (Fr')^{\frac{3}{2}} \cdot \left( \frac{d}{D} \right)^{\frac{7}{2}} . \tag{6}$$

## 3. Experimental

All measurements were carried out in transparent cylindrical vessels with dished bottom. The vessels were equipped with four radial baffles of width $b = 0.1 \cdot D$. The height of the liquid level was equal to the vessel diameter $H = D$. The geometrical configuration of the mixing equipment is shown in Fig. 1 and geometrical parameters are summarized in Table 1. The following axial impellers have been tested:

- Pitched three-blade turbines with various pitch angles $\alpha = 24°$, 35° a 45° (see Figs. 4a, 7c and 12)
- Standard pitched six-blade turbine with pitch angle $\alpha = 45°$
- Pitched blade turbine with diagonally folded blades with various blade number $i_L = 3$, 4 and 6, blade shape of this impeller type according to Czech standard CVS 69 1043 (see Figs. 4c and 8)
- Pitched cylindrical three-blade turbine according to Czech standard CVS 69 1042.2 (see Fig. 4b)
- Hydrofoil impeller LIGHTNIN type A310 (see Fig. 6)
- Marine propeller EKATO (see Fig. 7a)

- Propeller designed on Anhalt University of Applied Sciences / Hochschule Anhalt (FH) [8] (see Fig. 7b)

All impellers have been operated to pump the liquid downwards the vessel bottom.

Aqueous suspensions of glassy beads with large range of volumetric concentration $c_v$ and mean volumetric diameter $d_p$ of particles have been used as model suspensions. Particle size distribution and the mean diameters were characterised by a sieve and sedimentation analysis. Experimental conditions are summarized in Table 1. Critical impeller speed for suspension was determined visually according Zwietering definition [9]– no particle remains longer than 1 sec on the vessel bottom.

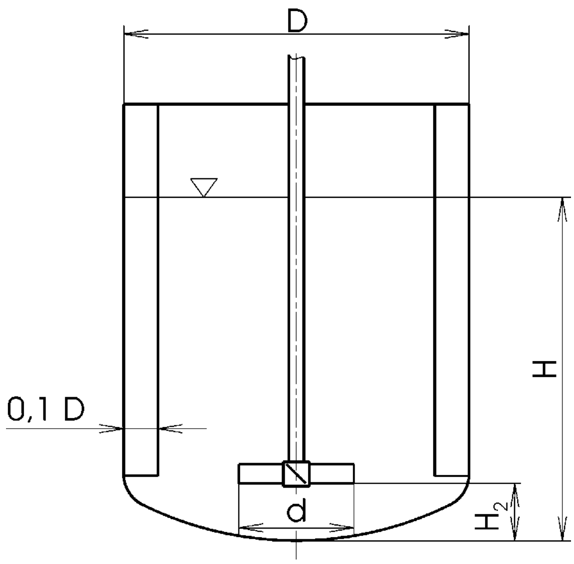



***Fig. 1.*** *Layout of geometrical arrangement of mixing equipment.*

***Table. 1.*** *Geometrical parameters of the mixing equipment and suspensions properties.*

| *Impeller* | $i_L$ | $\alpha$ | $\beta$ | $\gamma$ | *D [mm]* | *D/d* | $H_2/d$ | $d_p$ *[mm]* | $c_v$ |
|---|---|---|---|---|---|---|---|---|---|
| **3SL24** | 3 | 24° | - | - | 200 ÷ 300 | 3 | 0,5 | 0,15 ÷ 3,79 | 2,5 % ÷ 15 % |
| **3SL35** | | 35° | - | - | 200 ÷ 300 | 3 | 0,5 | 0,15 ÷ 3,79 | 2,5 % ÷ 15 % |
| **3SL45** | | 45° | - | - | 200 ÷ 300 | 3 | 0,5 | 0,15 ÷ 3,79 | 2,5 % ÷ 15 % |
| **6SL45** | 6 | | - | - | 200 ÷ 400 | 3 | 0,5 | 0,1 ÷ 1,5 | 2,5 % ÷ 40 % |
| **3RLL** | 3 | 67° | 25° | 48° | 200 ÷ 300 | 3 | 0,5 | 0,15 ÷ 3,79 | 2,5 % ÷ 15 % |
| **4RLL** | 4 | | | | 200 ÷ 300 | 3 | 0,5 | 0,15 ÷ 3,79 | 2,5 % ÷ 15 % |
| **6RLL** | 6 | | | | 200 ÷ 300 | 3 | 0,5 | 0,15 ÷ 3,79 | 2,5 % ÷ 15 % |
| **3TL** | 3 | - | - | - | 200 ÷ 300 (Po) | 3 | 0,5 | 0,15 ÷ 3,97 | 2,5 % ÷ 15 % |
| **A310** | | - | - | - | 300 | 3 | 0,5 | 0,15 ÷ 0,93 | 2,5 % ÷ 15 % |
| **MP (EKATO)** | | - | - | - | 385 | 2,67 | 0,5 ÷ 0,75 | 0,1 ÷ 1,0 | 2,5 % ÷ 15 % |
| **P (FH)** | | - | - | - | 385 | 2,67 | 0,5 ÷ 0,75 | 0,1 ÷ 1,0 | 2,5 % ÷ 15 % |

## 4. Experimental results

All measurements took place under the turbulent regime and results were evaluated in the form of dimensionless suspension and power characteristics. The primary experimental data obtained were transformed into dimensionless criteria and plotted as suspension characteristics. Suspension characteristics for the turbulent region are dependencies of modified Froude number $Fr'$ on the dimensionless particle size $d_p/D$ at constant volumetric particle concentration $c_v$.

The regression of the suspension characteristics was evaluated in the power form according to Eq. (2) and the appropriate straight lines are depicted in logarithmic coordinates (see example in Fig. 2). From these characteristics it can be seen that the exponent $\gamma_2$ for relatively large particles tends to zero. The plot of exponent $\gamma_1$ on the particle volumetric concentration $c_v$ indicates that it rises linearly with increasing $c_v$. The dependencies of coefficients $C_1$ and $C_2$ on particle concentration $c_v$ can be approximated in semi-logarithmic coordinates by straight lines. It is in agreement with correlations Eq. (4) and Eq. (5) proposed by Rieger [5, 6]. Example of experimental data evaluation is shown in Figs. 2 and 3. All these conclusions resulting from experimental data evaluation are valid for all tested axial impellers. Values of constants $A_i$, $B_i$, $\alpha_i$ and $\beta_i$ of Eq. (4) and Eq. (5) obtained by this way are listed in Table 2 for all tested axial impellers.

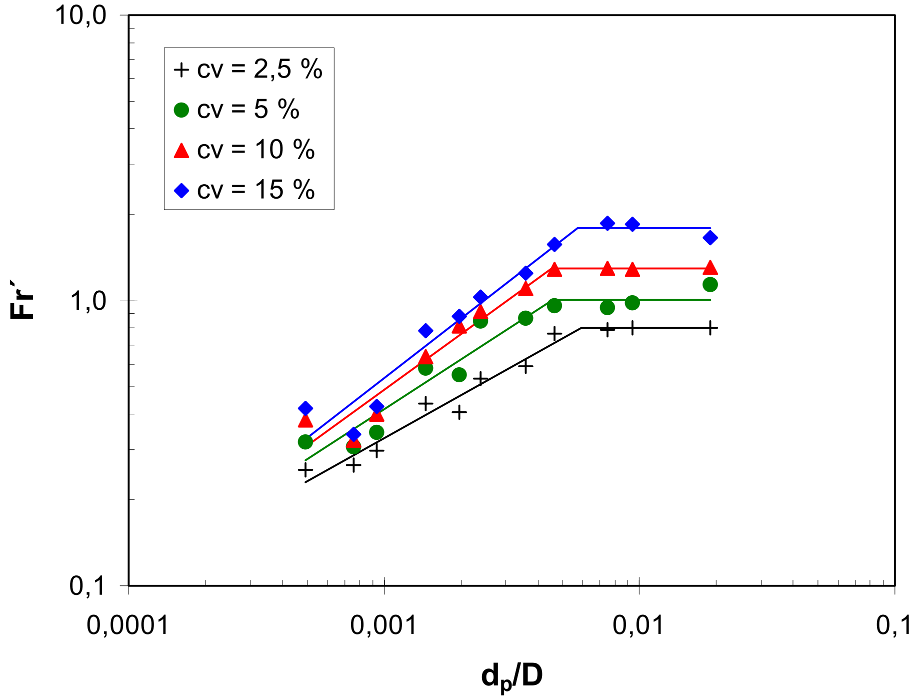
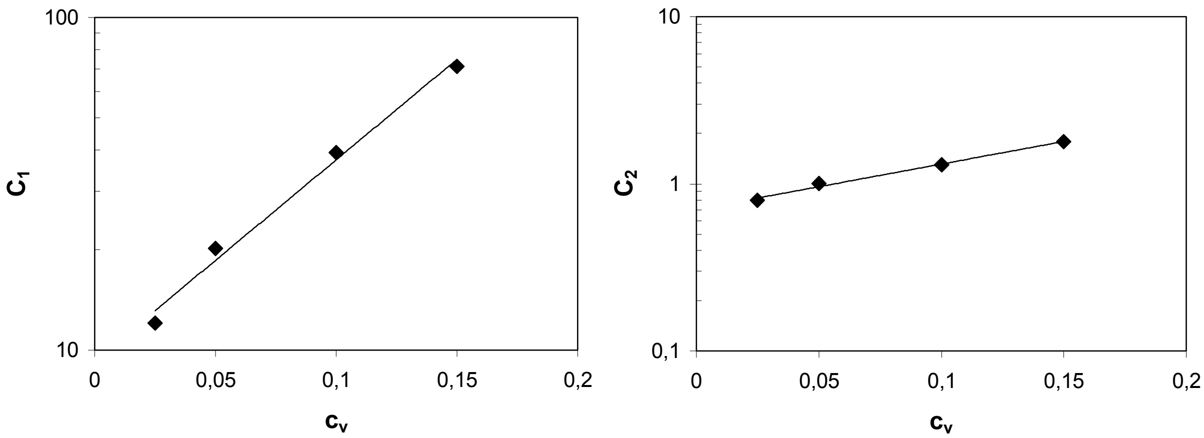



***Fig. 2.*** *Suspension characteristics Eq. (2) – pitched three-blade turbine with diagonally folded blades according to Czech standard CVS 69 1043.*



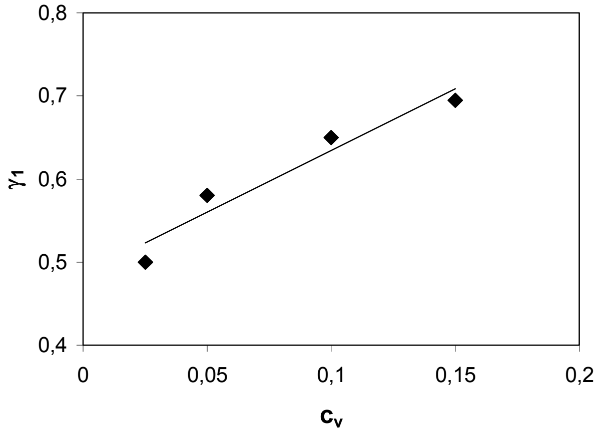



***Fig. 3.*** *Dependence of coefficients $C_i$ and $\gamma_i$ from Eq. (4) and Eq. (5) on volumetric particle concentration $c_v$ – pitched three-blade turbine with diagonally folded blades according to Czech standard CVS 69 1043.*

***Table. 2.*** *Values of constants $A_i$, $B_i$, $\alpha_i$ and $\beta_i$ of Eq. (4) and Eq. (5) for tested axial impellers.*

| *Impeller* | $H_2/d$ | $d_p/D$ | $c_v$ | *Re* |
|---|---|---|---|---|
| **3SL24** | 0,5 | $4{,}9\cdot10^{-4} \div 1{,}9\cdot10^{-2}$ | 2,5 % ÷ 15 % | 63300 ÷ 226800 |
| **3SL35** | 0,5 | $4{,}9\cdot10^{-4} \div 1{,}9\cdot10^{-2}$ | 2,5 % ÷ 15 % | 51000 ÷ 180600 |
| **3SL45** | 0,5 | $4{,}9\cdot10^{-4} \div 1{,}9\cdot10^{-2}$ | 2,5 % ÷ 15 % | 41000 ÷ 161600 |
| **6SL45** | 0,5 | $2{,}5\cdot10^{-4} \div 6{,}0\cdot10^{-3}$ | 2,5 % ÷ 40 % | 40800 ÷ 359500 |
| **3RLL** | 0,5 | $4{,}9\cdot10^{-4} \div 1{,}9\cdot10^{-2}$ | 2,5 % ÷ 15 % | 35600 ÷ 156100 |
| **4RLL** | 0,5 | $4{,}9\cdot10^{-4} \div 1{,}9\cdot10^{-2}$ | 2,5 % ÷ 15 % | 33900 ÷ 144300 |
| **6RLL** | 0,5 | $4{,}9\cdot10^{-4} \div 1{,}9\cdot10^{-2}$ | 2,5 % ÷ 15 % | 30300 ÷ 129100 |
| **3TL** | 0,5 | $7{,}6\cdot10^{-4} \div 2{,}0\cdot10^{-2}$ | 2,5 % ÷ 15 % | 40400 ÷ 121200 |
| **A310** | 0,5 | $4{,}9\cdot10^{-4} \div 3{,}1\cdot10^{-3}$ | 2,5 % ÷ 15 % | 78900 ÷ 244100 |
| **MP (EKATO)** | 0,5 | $2{,}6\cdot10^{-4} \div 2{,}6\cdot10^{-3}$ | 2,5 % ÷ 15 % | 126200 ÷ 321300 |
| | 0,75 | $2{,}6\cdot10^{-4} \div 2{,}6\cdot10^{-3}$ | 2,5 % ÷ 15 % | 112200 ÷ 286500 |
| **P (FH)** | 0,5 | $2{,}6\cdot10^{-4} \div 2{,}6\cdot10^{-3}$ | 2,5 % ÷ 15 % | 106500 ÷ 285700 |
| | 0,75 | $2{,}6\cdot10^{-4} \div 2{,}6\cdot10^{-3}$ | 2,5 % ÷ 15 % | 96100 ÷ 294300 |

| *Impeller* | $A_1$ | $B_1$ | $\alpha_1$ | $\beta_1$ | $A_2$ | $B_2$ | $\alpha_2$ | $\beta_2$ | *Ref.* |
|---|---|---|---|---|---|---|---|---|---|
| **3SL24** | 14,80 | 3,53 | 0,403 | 0,035 | 1,66 | 3,68 | 0 | 0 | [9] |
| **3SL35** | 8,58 | 5,63 | 0,399 | 0,323 | 1,00 | 4,37 | 0 | 0 | |
| **3SL45** | 11,67 | 7,40 | 0,487 | 0,660 | 0,954 | 4,36 | 0 | 0 | |
| **6SL45** | 5,38 | 13,9 | 0,43 | 1,63 | N/A | N/A | N/A | N/A | [10] |
| **3RLL** | 9,28 | 13,92 | 0,486 | 1,485 | 0,704 | 6,23 | 0 | 0 | [12] |
| **4RLL** | 8,80 | 9,29 | 0,500 | 0,789 | 0,617 | 5,48 | 0 | 0 | |
| **6RLL** | 5,98 | 10,07 | 0,472 | 0,879 | 0,463 | 6,84 | 0 | 0 | |
| **3TL** | 24,73 | 18,42 | 0,614 | 2,262 | 0,878 | 5,69 | 0 | 0 | [14, 15] |
| **A310** | 27,50 | 15,04 | 0,561 | 1,447 | N/A | N/A | N/A | N/A | [15, 16] |
| **MP (EKATO)** | 11,03 | 8,34 | 0,418 | 0,772 | N/A | N/A | N/A | N/A | [17] |
| | 9,47 | 10,36 | 0,432 | 1,009 | N/A | N/A | N/A | N/A | [17, 16] |
| **P (FH)** | 14,53 | 3,15 | 0,487 | 0 | N/A | N/A | N/A | N/A | [17] |
| | 17,88 | 9,35 | 0,545 | 0,791 | N/A | N/A | N/A | N/A | [17] |

The values of power number *Po* were found constant in turbulent region what is in a good agreement with generally understood theoretical considerations. Representative values of power numbers for the turbulent region have been evaluated along their limits on 95 % of confidence level and obtained results are listed in Table 3.

***Table. 3.*** *Values of power number Po of tested axial impellers.*

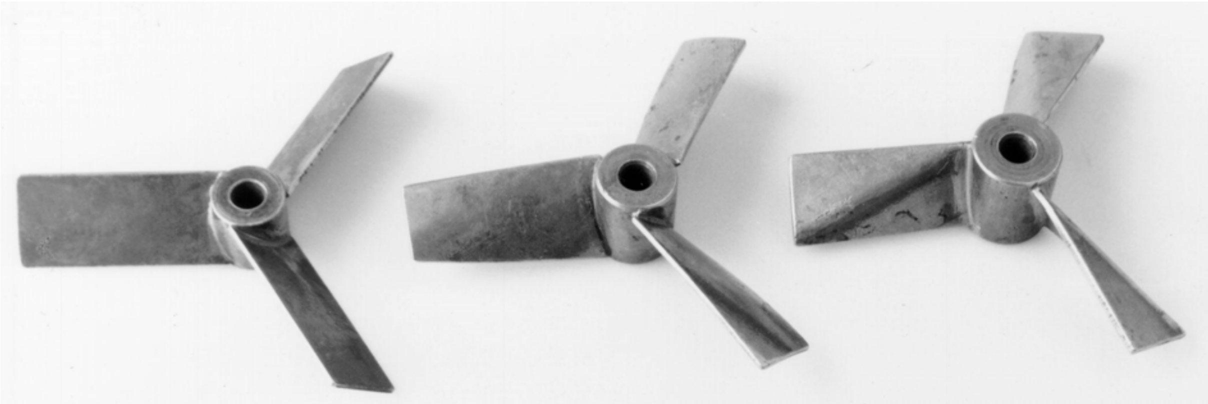
| *Impeller* | $H_2/d$ | *Re* | *Po* | *Ref.* |
|---|---|---|---|---|
| **3SL24** | 0,5 | 19300 ÷ 140700 | 0,37 ± 0,01 | [9] |
| **3SL35** | 0,5 | 19300 ÷ 107700 | 0,79 ± 0,04 | |
| **3SL45** | 0,5 | 14700 ÷ 97500 | 1,27 ± 0,04 | |
| **6SL45** | 0,5 | 80000 ÷ 120000 | 1,81 | [11] |
| **3RLL** | 0,5 | 24300 ÷ 129700 | 0,79 ± 0,03 | [13] |
| **4RLL** | 0,5 | 21900 ÷ 116300 | 0,99 ± 0,04 | |
| **6RLL** | 0,5 | 13700 ÷ 66700 | 1,34 ± 0,05 | |
| **3TL** | 0,5 | 47700 ÷ 126500 | 0,73 ± 0,02 | [14] |
| **A310** | 0,5 | 23500 ÷ 141300 | 0,34 ± 0,03 | [17] |
| **MP (EKATO)** | 0,5 | 34000 ÷ 202500 | 0,44 ± 0,04 | [17] |
| | 0,75 | 33800 ÷ 176300 | 0,39 ± 0,04 | [17] |
| **P (FH)** | 0,5 | 34000 ÷ 183900 | 0,45 ± 0,05 | [17] |
| | 0,75 | 34000 ÷ 174900 | 0,40 ± 0,04 | [17] |

## 5. Discussion

### *5.1. Effect of the blade shape on particle suspension with three-blade axial impellers*

*5.1.1. Impellers according to Czech standards*

First of all selected impellers with profiled blades according to Czech standards were compared with standard three-blade turbine. These compared impellers are shown in the following Fig. 4.



***a)*** ***b)*** ***c)***

***Fig. 4.*** *Three-blade axial impellers according to Czech standards:* ***a)*** *– Standard pitched three-blade turbine with pitch angle $\alpha = 45°$,* ***b)*** *– Pitched cylindrical three-blade turbine according to CVS 69 1042.2,* ***c)*** *– Pitched three-blade turbine with diagonally folded blades according to CVS 69 1043.*

The pitched three-blade turbine with diagonally folded blades has the lowest values of just-suspended impeller speed in the whole measured range of dimensionless particle diameter $d_p/D$ and the volumetric concentration of solid phase $c_v$. The values of just-suspended impeller speed are practically the same for other used impellers in lower particle volumetric concentrations. However, the cylindrical three-blade turbine has the highest values of critical impeller speed for higher concentrations of solid phase.

The suspension efficiency of impellers used in experiments is compared by means of dimensionless power consumption necessary for off-bottom particle suspension. From comparison of the dimensionless criterion $\pi_s$ (see Fig. 5) it follows that the pitched three-blade turbine with diagonally folded blades requires lower power consumption for suspension than the pitched three-blade turbine and the pitched cylindrical three-blade turbine. The standard pitched three-blade turbine has the highest energetic requirements for off-bottom particle suspension. This is valid for the whole measured range of the dimensionless particle diameter $d_p/D$ and the volumetric concentration of solid phase $c_v$.

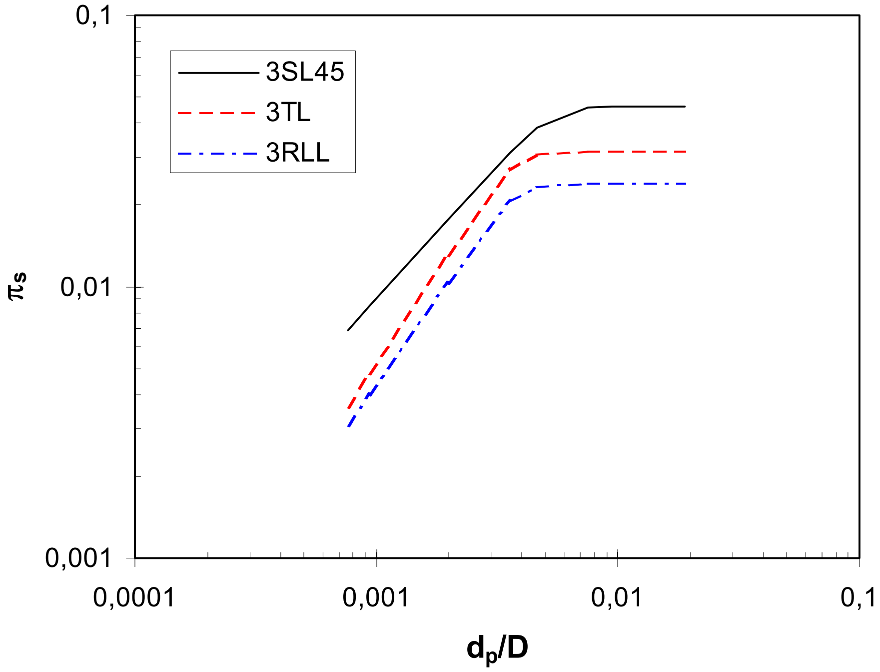



***Fig. 5.*** *Dependence of the dimensionless power consumption necessary for off-bottom particle suspension $\pi_s$ of three-blade axial impellers according to Czech standards on the dimensionless particle diameter $d_p/D$ for particle volumetric concentration $c_v$ = 10 %.*

*5.1.2. Hydrofoil Impellers*

During last 15 years the leading mixing manufacturers developed so called hydrofoil impellers having the blade pitch varying from 45° at the hub to about 22° at the impeller tip. Selected types of hydrofoil impellers are shown in Fig. 6 and 7. Axial impellers of more simple design (standard pitched three-blade turbine with pitch angle $\alpha$ = 45°, see Figs. 4a and 7a) and pitched three-blade turbine with diagonally folded blades (see Figs. 4c and 8) and their suspension ability were taken as a standard for comparison with impellers having more sophisticated design.

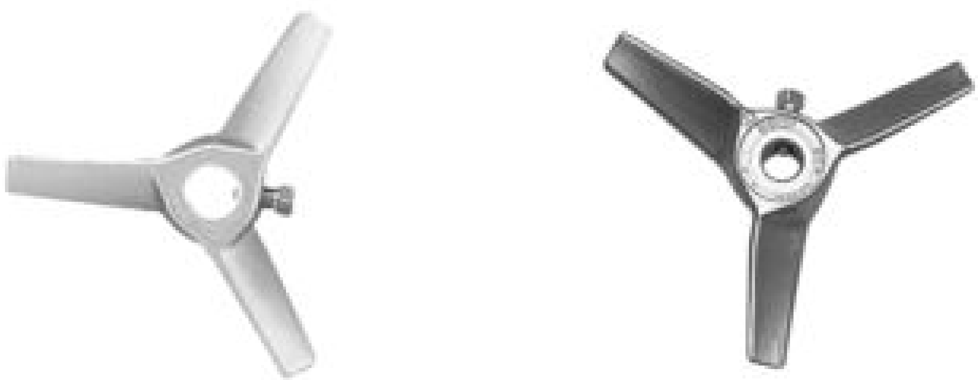
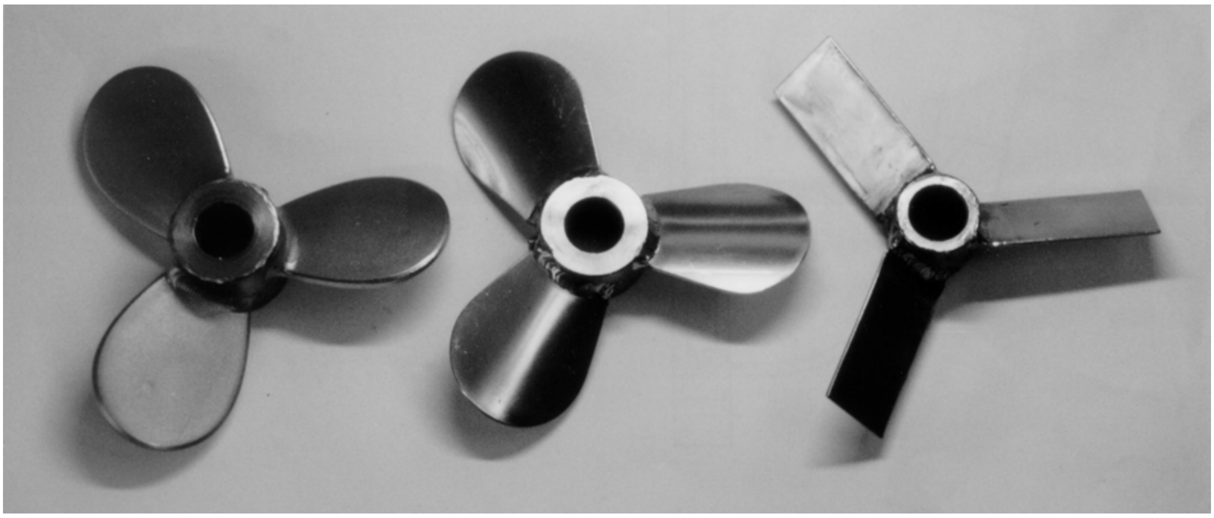


***Fig. 6.*** *Hydrofoil impeller LIGHTNIN type A310.*



***a)*** ***b)*** ***c)***

***Fig. 7.*** *Comparison of propeller blade shape and standard pitch blade:* ***a)*** *– Marine propeller EKATO,* ***b)*** *– Propeller designed on Anhalt University of Applied Sciences / Hochschule Anhalt (FH),* ***c)*** *– standard pitched three-blade turbine with pitch angle* $\alpha = 45°$.

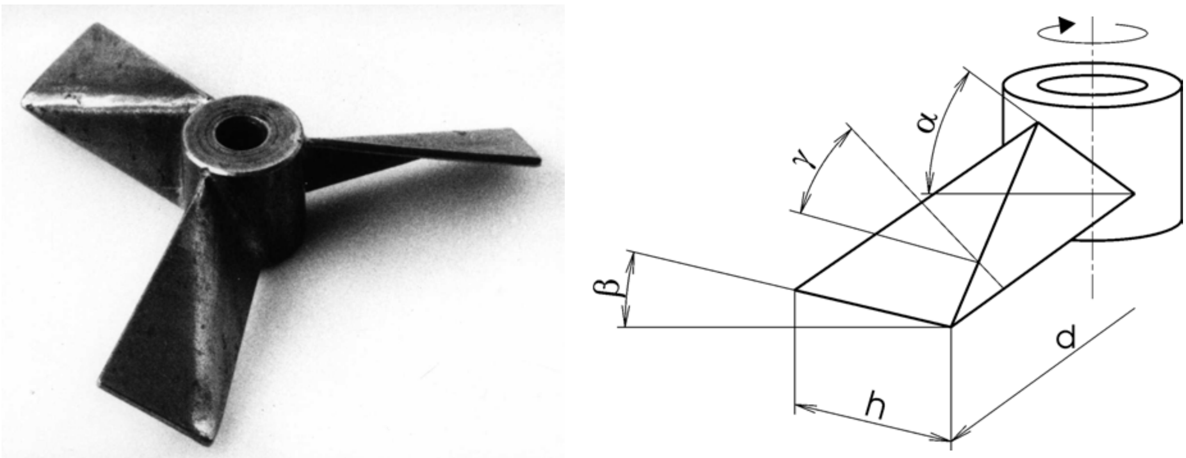



***Fig. 8.*** *Pitched three-blade turbine with diagonally folded blades and blade shape of this impeller type according to Czech standard CVS 69 1043* ($\alpha = 67°$; $\beta = 25°$; $\gamma = 48°$; $h/d = 0.2$)

From Fig. 9 it is seen that both Marine propeller EKATO and propeller impeller designed on Anhalt University of Applied Sciences / Hochschule Anhalt (FH) have better suspension efficiency when operated at reasonably higher impeller clearance, position $H_2/d$ = 0.75 was found significantly better than $H_2/d$ = 0.5. It is probably due to the propeller hydraulics that has been originally designed for operation in an infinite space. The effect of impeller clearance was also tested for impeller LIGHTNIN A310, however, practically no difference in suspension efficiency was observed within the range $H_2/d = \langle 0.5 \div 0.75 \rangle$.

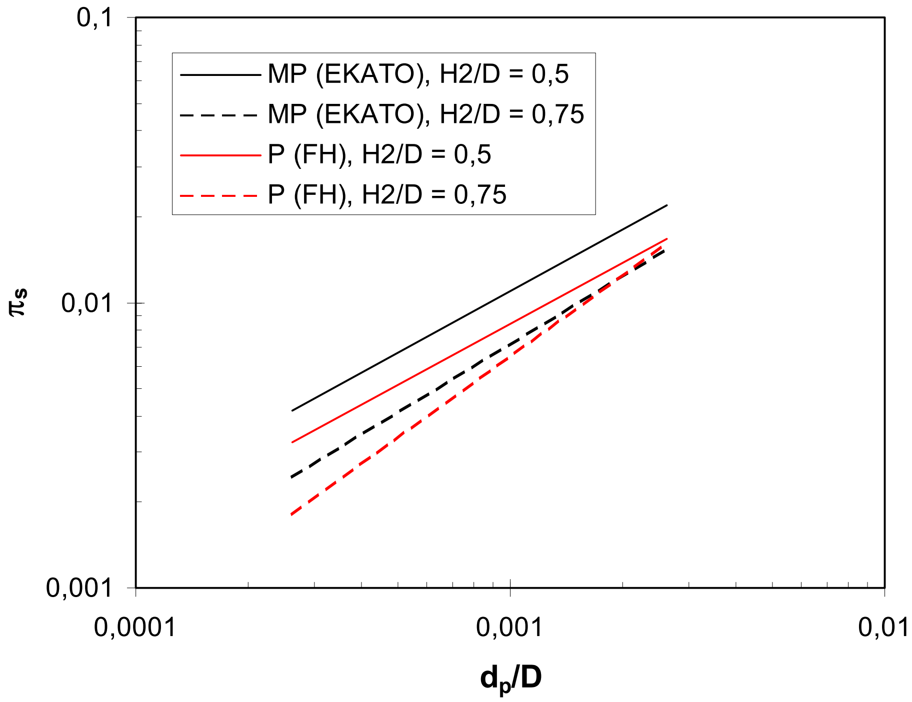



***Fig. 9.*** *Dependence of the dimensionless power consumption necessary for off-bottom particle suspension* $\pi_S$ *of tested propellers on the dimensionless particle diameter* $d_p/D$ *for particle volumetric concentration* $c_v = 10$ *%.*

The final comparison of suspension efficiency by means of the dimensionless power consumption necessary for particle suspension of single tested impellers is seen from Fig. 10 for particle concentrations 10 % by volume. To be fair, all impellers were compared at the impeller clearances giving the best suspension efficiency. From this comparison of energetic requirements it follows that hydrofoil impellers have higher suspension efficiency than the standard 45° pitched-blade impellers. Moreover, all hydrofoil impellers have roughly the same suspension efficiency when compared at optimum impeller clearance. Geometrical simplicity of the pitched three-blade turbine with diagonally folded blades according to Czech standard CVS 69 1043 at the comparable suspension efficiency with the other hydrofoil impellers makes this impeller the most favourable one.

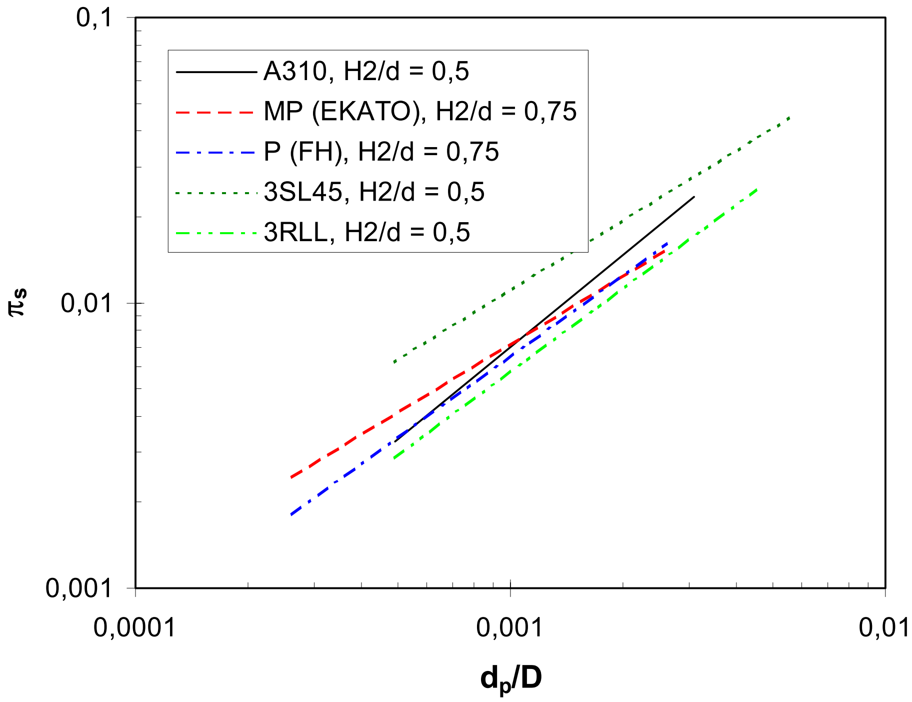



***Fig. 10.*** *Dependence of the dimensionless power consumption necessary for off-bottom particle suspension $\pi_s$ of three-blade axial impellers on the dimensionless particle diameter $d_p/D$ for particle volumetric concentration $c_v$ = 10 %.*

### *5.2. Effect of the blade number on particle suspension with pitched blade turbine with diagonally folded blades*

The pitched blade turbine with diagonally folded blades is a high efficiency impeller (see Fig 10), moreover, it has very simple blade shape. For this reason experiments were focused on effect of the blade number on particle suspension with this impeller type. The experiments were carried out with pitched blade turbines with diagonally folded blades having three, four and six blades. Impeller blade shape was shown in Fig. 8.

From comparison of the suspension efficiency by means of the dimensionless criterion $\pi_s$ (see Fig. 11) it can be said that dimensionless power consumption necessary for particle suspension is practically independent of the blade number of pitched blade turbine with diagonally folded blades. Values of the just-suspended impeller speed decrease with increasing blade number of this impeller type. However, impellers with lower blade number have lower torgue. It is valid for the whole measured range of the dimensionless particle diameter $d_p/D$ and the volumetric concentration of solid phase $c_v$.

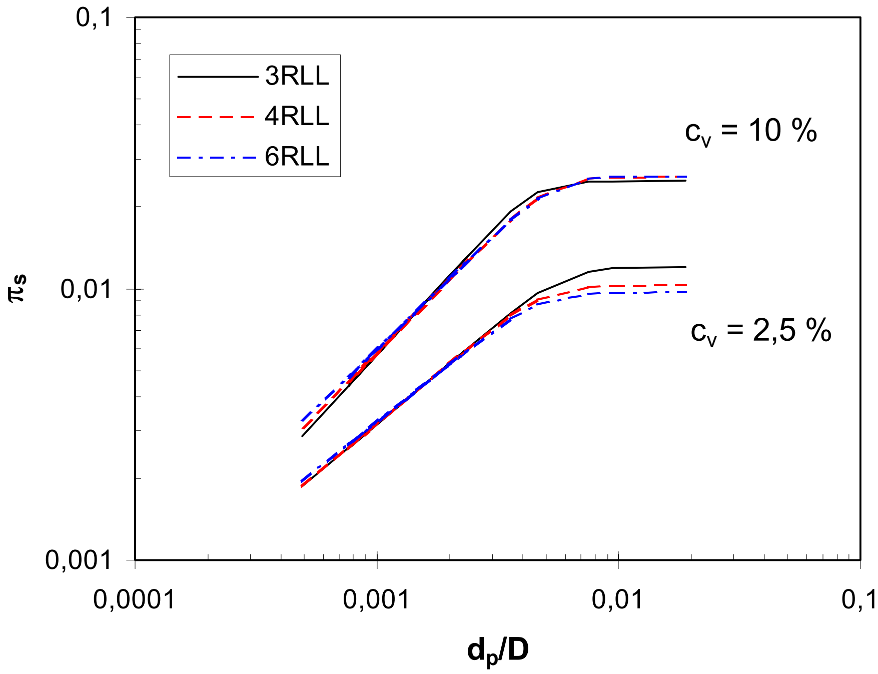



***Fig. 11.*** *Dependence of the dimensionless power consumption necessary for off-bottom particle suspension* $\pi_s$ *of pitched blade turbine with diagonally folded blades on the dimensionless particle diameter* $d_p/D$.

### *5.3. Effect of the pitch angle on particle suspension with pitched three-blade turbine*

The pitched blade turbine is one of the simplest types of axial-flow impellers. It is used very frequently in a chemical industry. For this reason we decided to investigate the effect of the pitch angle on particle suspension with pitched three-blade turbine. Pitch blade angles α = 24°, 35° and 45° were tested and compared. The pitched three-blade turbine is shown in the Fig. 12.

The dependence of the dimensionless criterion $\pi_s$ on the dimensionless particle diameter $d_p/D$ for the volumetric concentration of solid particles $c_v$ = 2.5 % and 10 % is shown in Fig. 13. From the comparison of the suspension efficiency in the whole measured range of the dimensionless particle diameter $d_p/D$ and the particle volumetric concentration $c_v$ it can be seen that the pitch blade angle has minimum effect on the suspension efficiency in region of the relatively fine particles. The pitched three-blade turbine with blade angle $\alpha$ = 45° has the highest energetic requirement for suspension among the compared pitched blade impellers in the region of relatively large particles. It follows from different mechanism of particle suspension in region of relatively fine and large particles, as it was shown in [18]. Values of the just-suspended impeller speed decrease with increasing pitch angle of this impeller type.

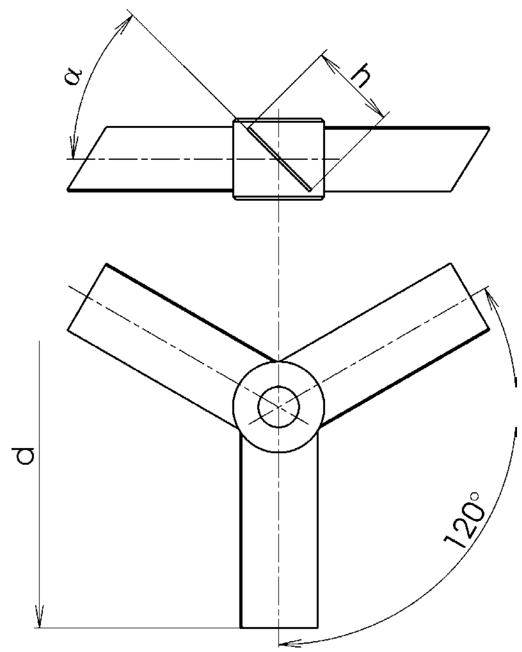



*Fig. 12. Pitched three-blade turbines with various pitch angles α = 24°, 35° and 45°.*

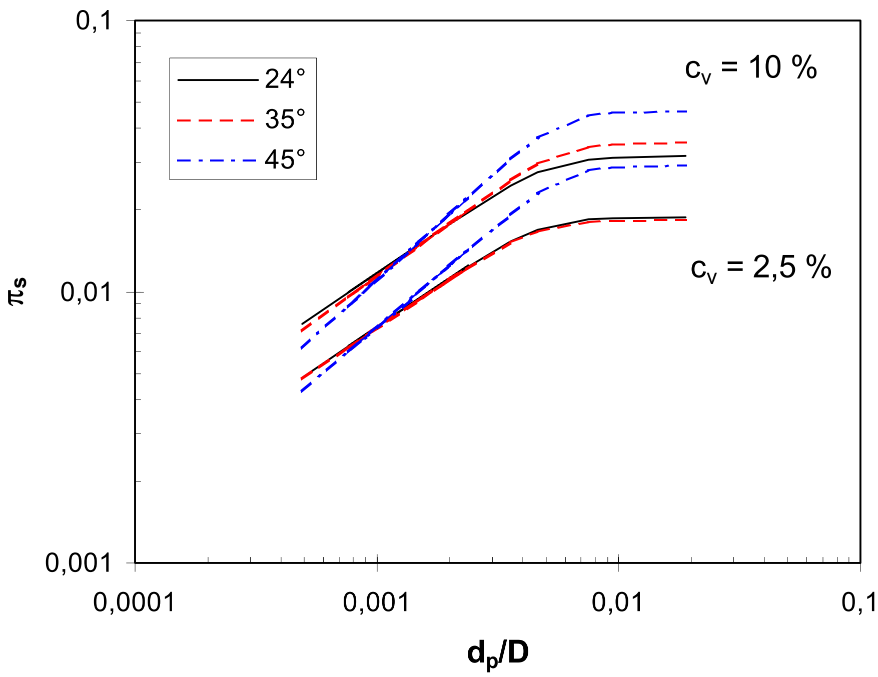



***Fig. 13.*** *Dependence of the dimensionless power consumption necessary for off-bottom particle suspension $\pi_s$ of pitched three-blade turbines with various pitch angles $\alpha$ = 24°, 35° and 45° on the dimensionless particle diameter $d_p/D$.*

## 6. Conclusions

Very important parameters for designing of mixing apparatuses for suspensions are the critical (just-suspended) impeller speed and power consumption necessary for off-bottom suspension of solid particles. On the basis of numerous suspension measurements there were proposed correlations for calculation of just-suspended impeller speed of eleven impeller types and geometries in the wide range of concentrations and particle diameters.

The following conclusions might be drawn from comparison of the suspension efficiency by means of the dimensionless power consumption necessary for off-bottom suspension of solid particles:

- Hydrofoil impellers have higher suspension efficiency than the standard 45° pitched-blade impellers.
- All hydrofoil impellers have roughly the same suspension efficiency when compared at optimum impeller clearance.
- Propellers are more sensitive on impeller clearance than the other impellers in investigated range.
- Geometrical simplicity of the pitched three-blade turbine with diagonally folded blades according to Czech standard CVS 69 1043 at the comparable suspension efficiency with the other hydrofoil impellers makes this impeller the most favourable one.
- Dimensionless power consumption necessary for particle suspension is practically independent of the blade number of pitched blade turbine with diagonally folded blades.
- Pitch blade angle has minimum effect on the suspension efficiency in region of the relatively fine particles. The pitched three-blade turbine with blade angle $\alpha$ = 45° has the highest energetic requirement for suspension among the compared pitched blade impellers in the region of relatively large particles.

**List of symbols**

| | | |
|---|---|---|
| $A_i$ | coefficients of equation (4) | [1] |
| $B_i$ | coefficients of equation (4) | [1] |
| $b$ | baffle width | [m] |
| $C_i$ | coefficients of equations (2), (3) and (4) | [1] |
| $c_V$ | mean volumetric concentration of solid phase | [1] |
| $D$ | vessel diameter | [m] |
| $d$ | impeller diameter | [m] |
| $d_p$ | mean volumetric particle diameter | [m] |
| $Fr'$ | modified Froude number $Fr' = \frac{\rho n_c^2 d}{g \Delta\rho}$ | [1] |
| $g$ | acceleration due to gravity | [m·s$^{-2}$] |
| $H$ | height of the liquid level | [m] |
| $H_2$ | impeller off-bottom clearance (measured from the lowest point on the blades) | [m] |
| $h$ | width of impeller blade | [m] |
| $n_c$ | critical (just-suspended) impeller speed | [s$^{-1}$] |
| $P$ | power consumption | [W] |
| $Po$ | power number $Po = \frac{P}{\rho_{su} n^3 d^5}$ | [1] |
| $Re$ | Reynolds number $Re = \frac{nd^2\rho}{\mu}$ | [1] |

*Greek symbols*

| | | |
|---|---|---|
| $\alpha, \beta, \gamma$ | pitch angles | [°] |
| $\alpha_i$ | coefficients of equation (5) | [1] |
| $\beta_i$ | coefficients of equation (5) | [1] |
| $\gamma_i$ | coefficients of equations (2), (3) and (5) | [1] |

| | | |
|---|---|---|
| $\mu$ | dynamic viscosity | [Pa·s] |
| $\pi_s$ | dimensionless power consumption necessary for particle suspension | [1] |
| | $\pi_s = \frac{P}{\rho_{su}}\left(\frac{\rho}{g\Delta\rho}\right)^{\frac{3}{2}}\left(\frac{1}{D}\right)^{\frac{7}{2}}$ | |
| $\rho$ | liquid density | [kg·m$^{-3}$] |
| $\rho_{su}$ | suspension density | [kg·m$^{-3}$] |
| $\Delta\rho$ | solid – liquid density difference | [kg·m$^{-3}$] |

**Impeller geometry abbreviations**

| | |
|---|---|
| **3SL24** | Pitched three-blade turbine with pitch angle $\alpha = 24°$ |
| **3SL35** | Pitched three-blade turbine with pitch angle $\alpha = 35°$ |
| **3SL45** | Pitched three-blade turbine with pitch angle $\alpha = 45°$ |
| **6SL45** | Pitched six-blade turbine with pitch angle $\alpha = 45°$ |
| **3RLL** | Pitched three-blade turbine with diagonally folded blades |
| **4RLL** | Pitched four-blade turbine with diagonally folded blades |
| **6RLL** | Pitched six-blade turbine with diagonally folded blades |
| **3TL** | Pitched cylindrical three-blade turbine |
| **A310** | Hydrofoil impeller LIGHTNIN type A310 |
| **MP (EKATO)** | Marine propeller EKATO |
| **P (FH)** | Propeller designed on Anhalt University of Applied Sciences / Hochschule Anhalt (FH) |

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