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Short communication

Effect of particle content on agitator speed for off-bottom suspension

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Abstract

This paper deals with the effect of particle content on agitator speed for off-bottom suspension. The measurements were carried out with a pitched six-blade turbine in a flat-bottomed vessel equipped with four baffles. An equation for off-bottom suspension speed was obtained for volumetric particle content up to 45%.

Keywords: Agitator speed; Off-bottom suspension; Volumetric particle content

1. Introduction

Mixing of suspensions is one of the most frequent operations occurring in mixing equipment. A very important parameter for designing of mixing apparatuses for suspensions is the critical impeller speed necessary for off-bottom suspension of particles. The results of critical impeller speed measurements for a wide range of Reynolds numbers and particle diameters, for two values of particle volumetric concentrations 2.5 and 10%, were presented in Ref. [1]. On the basis of an inspection analysis of the governing equations we proposed for calculation of the critical agitator speed for geometrically similar mixing equipment, and given particle content, in the turbulent regime the dimensionless equation

$$\mathrm{Fr}' = C\left(\frac{d_\mathrm{p}}{D}\right)^c \qquad (1)$$

where modified Froude number $\mathrm{Fr}'=n^2 d\rho/g\Delta\rho$. On the basis of the particle-to-vessel diameter ratio d_p/D, the experimental results can be subdivided into two regions with different values of C and c coefficients. For calculation of critical impeller speed in equipment of industrial size, the region of small d_p/D values are important. The aim of this paper is to deal with the effect of particle concentration on critical impeller speed in this region.

2. Experimental

Experiments were carried out on a mixing apparatus driven by a dc electrical motor with a thyristor speed regulation in the range 100–3000 min^{-1}. The speed was measured by means of a photoelectric pick-up.

The measurements were carried out in flat-bottomed glass vessels with an inside diameter D=200 and 300 mm equipped with four baffles of width w=0.1D. A pitched six-blade turbine with blade angle 45° was used in the experiments. The ratio of vessel to agitator diameter was D/d=3. The impeller off-bottom clearance H_2=0.5d. The filling height in the vessel was equal to the vessel diameter.

The measurements were carried out in water suspensions of glass ballotine with particle diameter in the range from 0.072 to 2 mm and solid phase volumetric concentration c_v in the range from 2.5 to 45%. The critical impeller speed was determined visually based on observation of the sediment at the bottom of the vessel. This experimental method was described in detail in [1]. Good agreement between such determined critical impeller speed and the same based on Zwietering's definition, which is however applicable for large particles only, was proved.

3. Results

All results of critical impeller speed measurements were plotted in the form of modified Froude number Fr′ depen-

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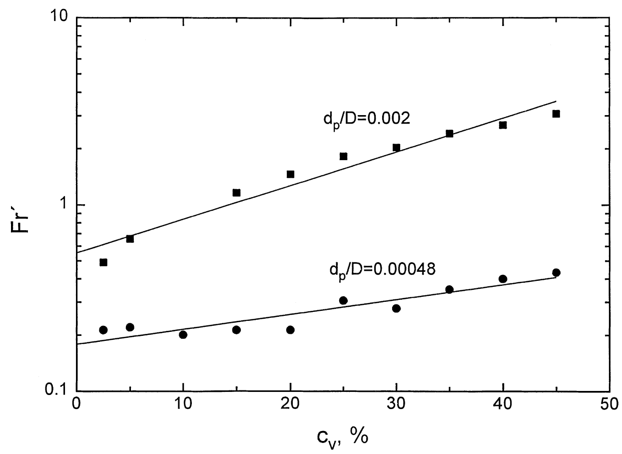

Fig. 1. Dependence of Fr′ on volumetric solid phase content c_v.

dence on volumetric concentration c_v. The typical form of this dependence for the two particle sizes characterized by d_p/D ratio is illustrated in Fig. 1. From this figure it can be seen that the dependence in semilogarithmic coordinates is a straight line and for this reason it can be expressed in the form

$$\mathrm{Fr}' = \mathrm{Fr}'_0 \exp(bc_\mathrm{v}) \tag{2}$$

From Fig. 1 it can also be seen that the dependence is more pronounced for relatively greater particles. From the semilogarithmic plot of coefficient b on d_p/D shown in Fig. 2, it follows that it can be described by the straight line equation

$$b = 15.7 + 1.84 \ln\left(\frac{d_\mathrm{p}}{D}\right) \tag{3}$$

The corresponding logarithmic plot of Fr'_0 on d_p/D in Fig. 3 can be described by the relation

$$\mathrm{Fr}'_0 = 11.4\left(\frac{d_\mathrm{p}}{D}\right)^{0.54} \tag{4}$$

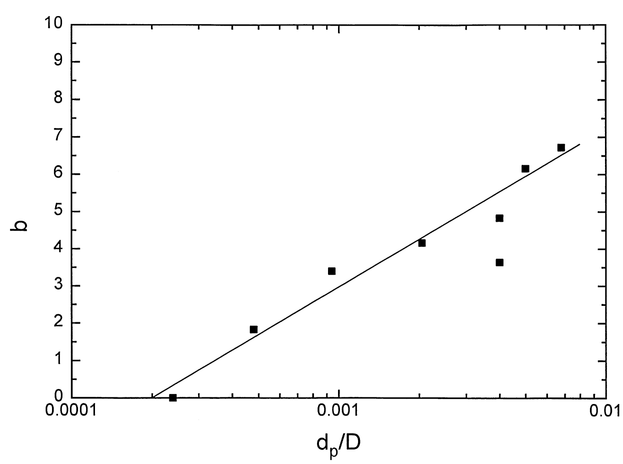

Fig. 2. Dependence of coefficient b on d_p/D.

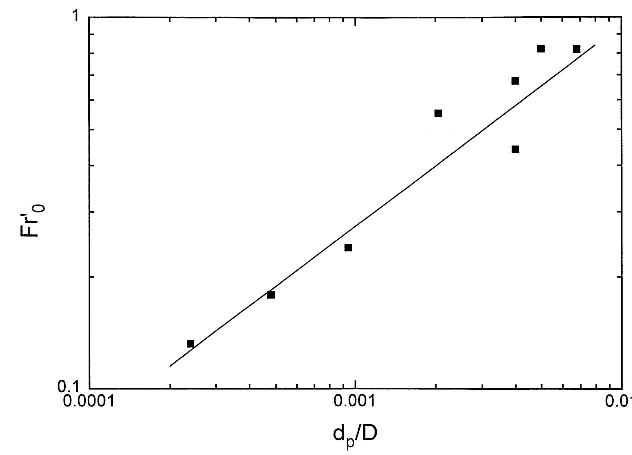

Fig. 3. Dependence of Fr'_0 on d_p/D.

Substituting Eqs. (4) and (3) into Eq. (2) we obtain after rearrangement

$$\mathrm{Fr}' = 11.4\left(\frac{d_\mathrm{p}}{D}\right)^{0.54}\left[6.58\times10^{6}\left(\frac{d_\mathrm{p}}{D}\right)^{1.84}\right]^{c_\mathrm{v}} \tag{5}$$

The last equation can also be written in the form of Eq. (1) with

$$C = 11.4(6.58\times10^{6})^{c_\mathrm{v}} \tag{6a}$$

$$c = 0.54 + 1.84c_\mathrm{v} \tag{6b}$$

from which it follows that coefficients C and c increase with increasing particle content c_v.

4. Discussion

The experimental and calculated dependence of Fr′ on d_p/D for two values of particle concentration c_v=5 and 20% is shown in Fig. 4. From this figure it can be seen that dependence of the critical speed on the relative particle size d_p/D is more pronounced for greater particle contents c_v. The critical speed is practically independent of c_v for relatively small particles and increases with c_v for greater particles (it can also be seen from Fig. 1).

Comparison of Eq. (5) with experimental results presented for c_v=2.5% in [1] is shown in Fig. 5 and a relatively good agreement is obvious.

Comparison of present results with those of other authors is difficult due to the fact that in most papers since the pioneering well-known paper of Zwietering [2] the effect of particle content is expressed in power form ($n \sim c_\mathrm{m}{}^{\alpha}$) which leads to unrealistic zero critical speed at solid content limiting to zero. Further weakness of Zwietering's correlation consists of the fact that the exponent above the solid concentration is independent of the particle diameter which is in contrast with experimental results. A direct comparison of our experimental results with Zwietering's equation is not

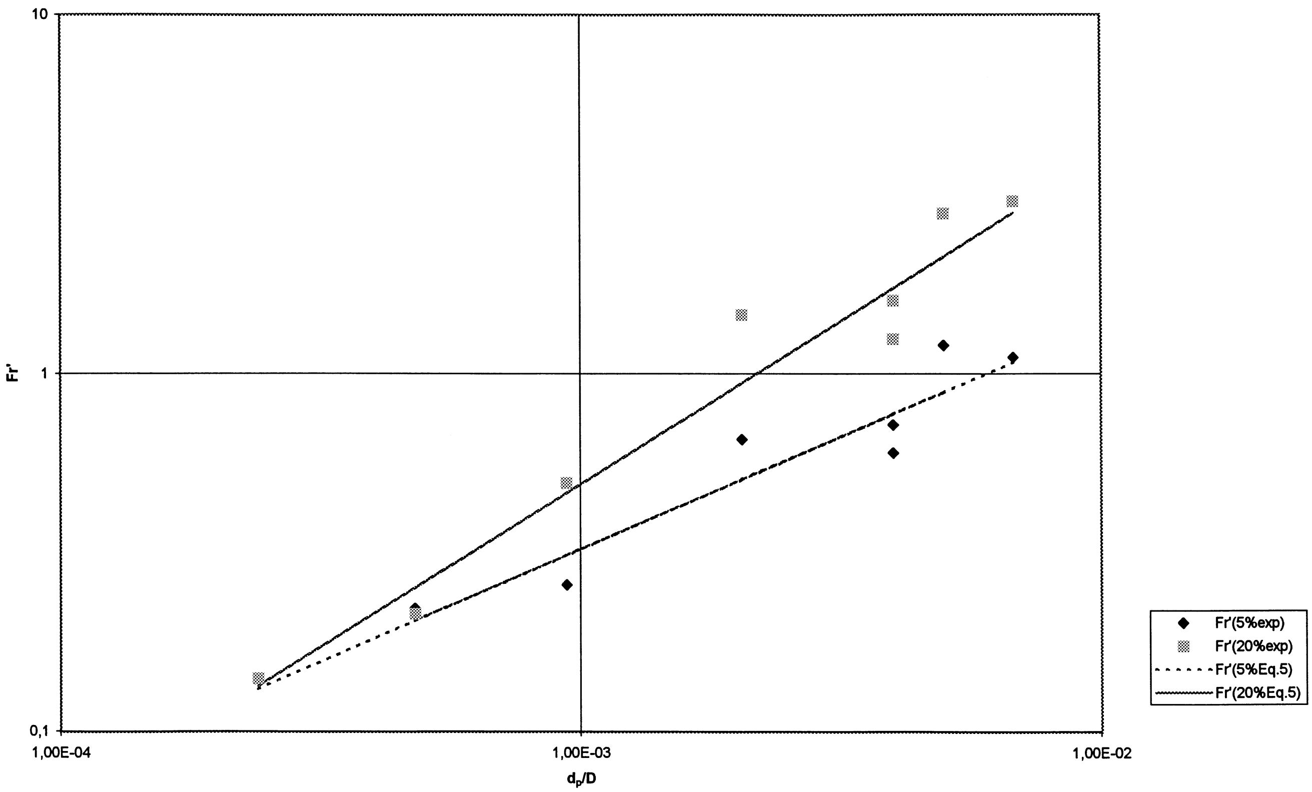

Fig. 4. Dependence of experimental and calculated Fr′ values on d_p/D.

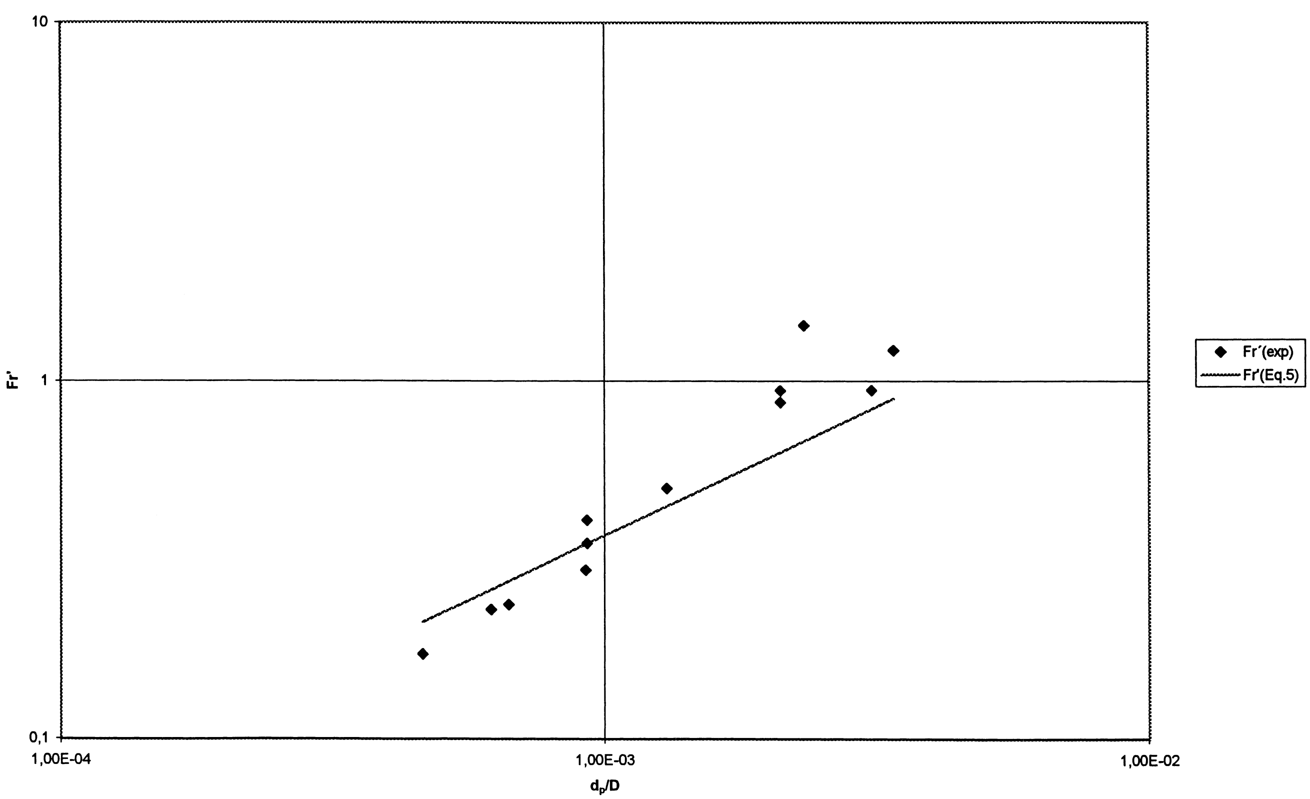

Fig. 5. Comparison of experimental results presented in Ref. [1] with Eq. (5).

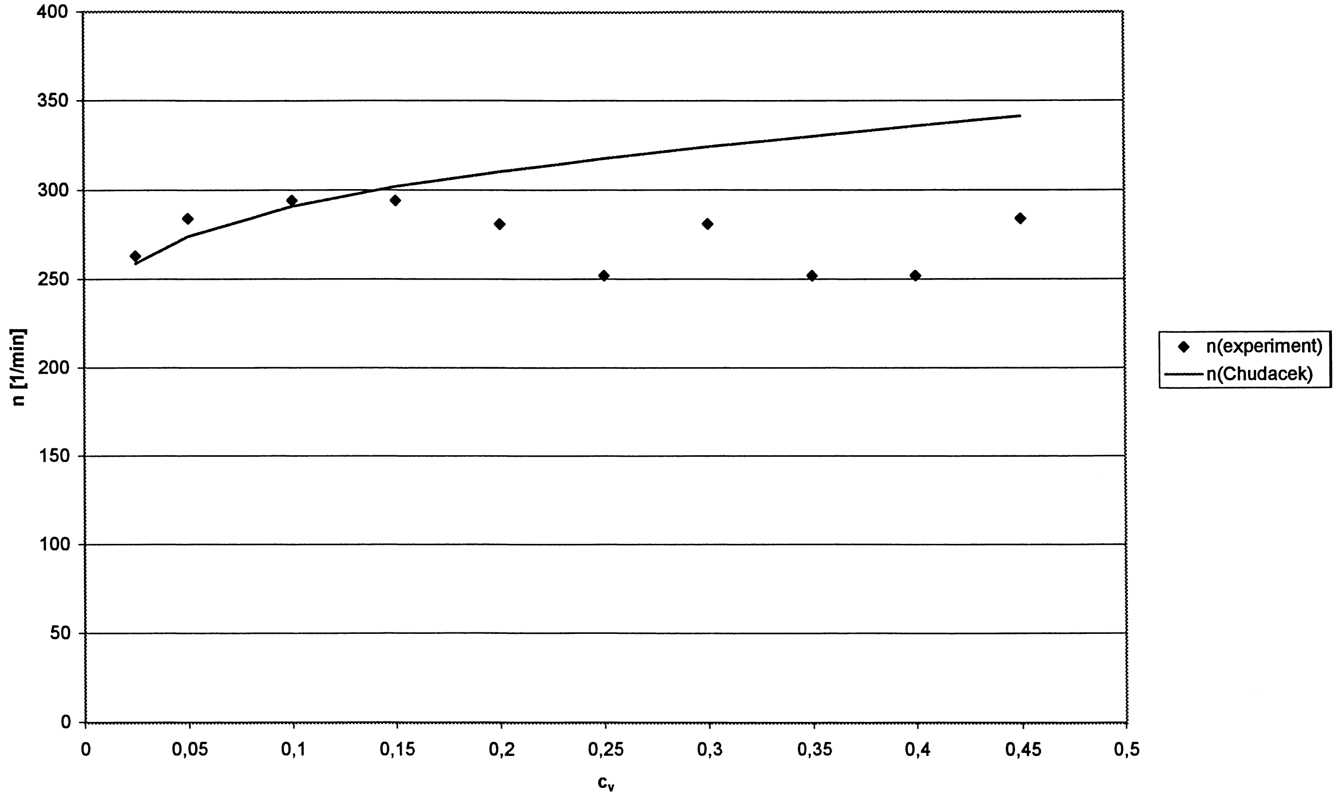

Fig. 6. Comparison of experimental data with prediction by Chudacek [3] for small particles d_p=0.072 mm.

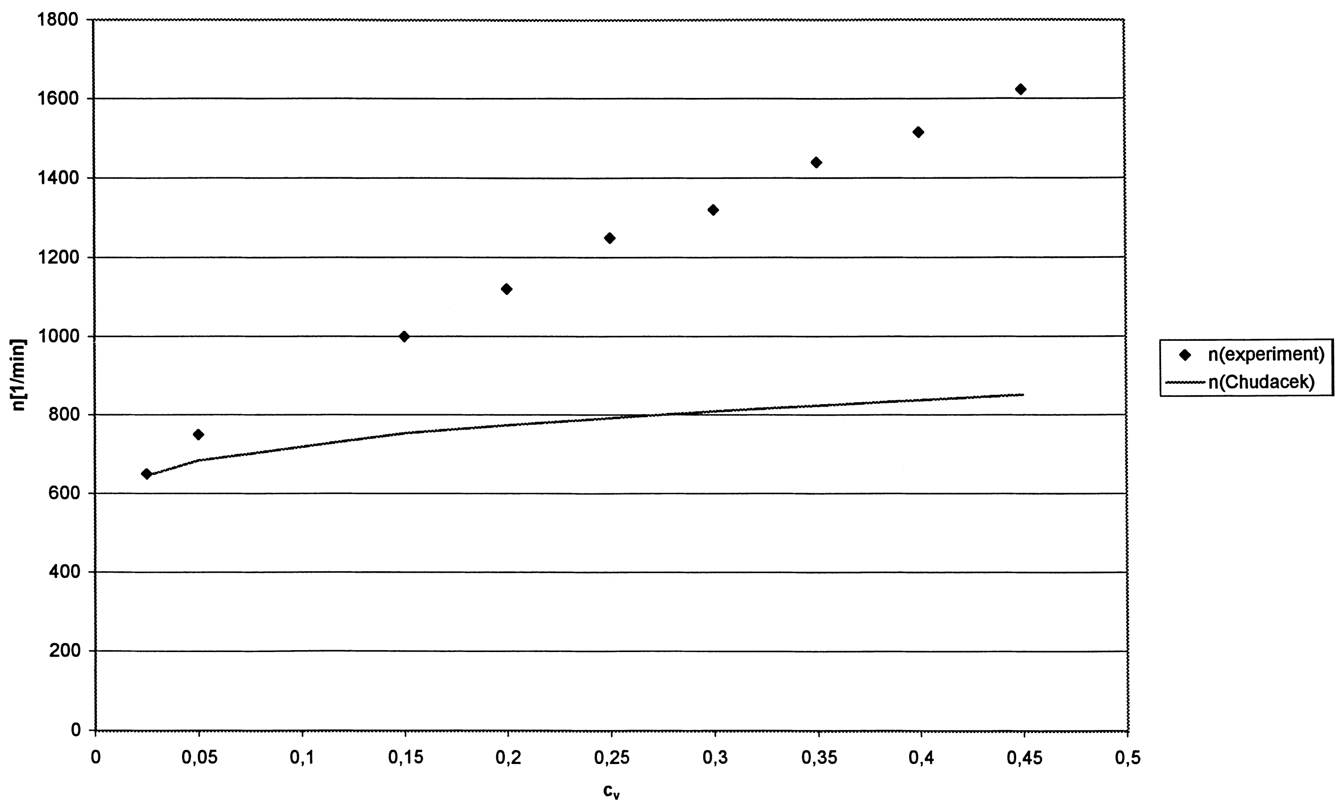

Fig. 7. Comparison of experimental data with prediction by Chudacek [3] for particles d_p=0.4 mm.

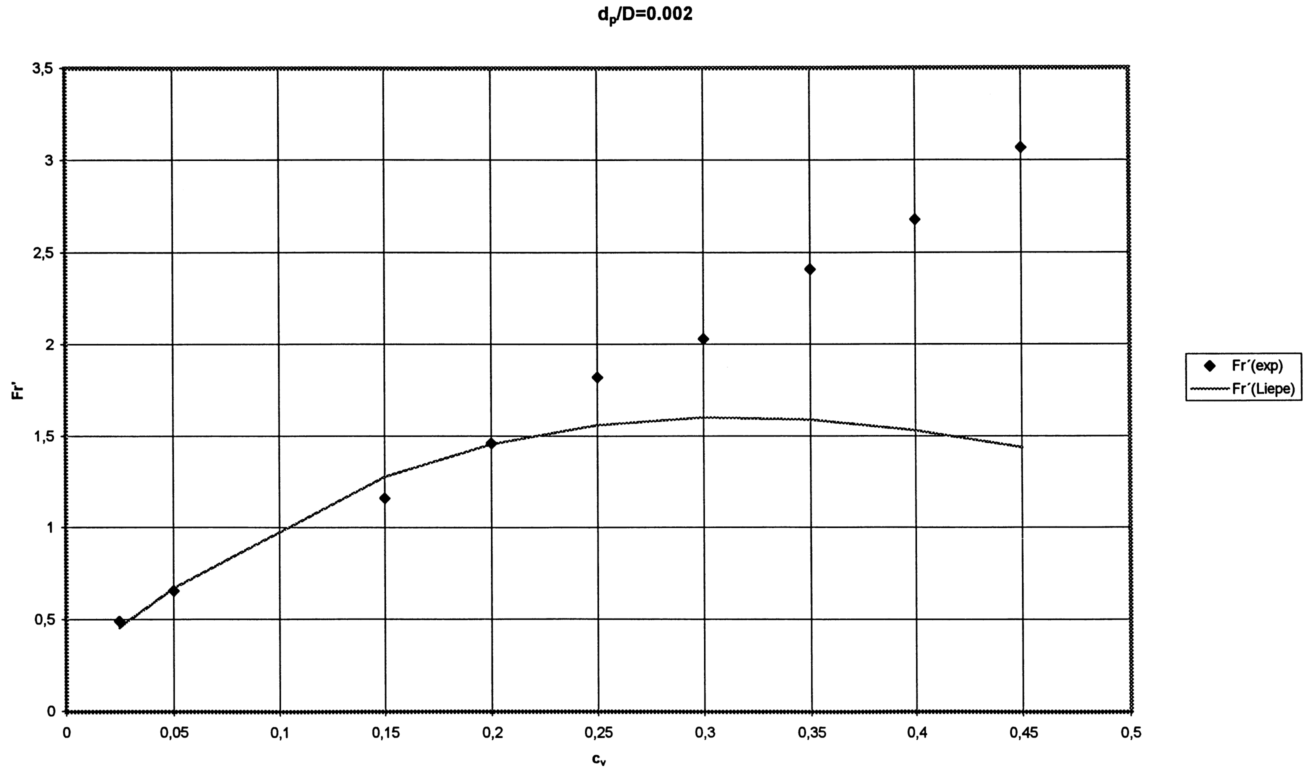

Fig. 8. Comparison of experimental results with values calculated by Liepe and Koschek [4].

possible because of different impellers tested. The only possibility of the comparison is offered by results presented by Chudacek [3], who evaluated his measurements according to Zwietering's approach. From Figs. 6 and 7 it is seen that the critical impeller speed calculated by Chudacek is overestimated for fine particles and underestimated for large ones.

Also relations based on velocity of hindered sedimentation are not in good agreement with experiments (especially for greater particle contents) as it can be seen from Fig. 8 in which comparison of experimental results with values calculated by Liepe and Koschek [4] is shown.

From Eq. (4) it follows that $n \sim d^{-0.77}$ which means that at small particle content, the often used scale up at constant specific power ($n \sim d^{-0.67}$) is on the safe side. For greater particle content the scale-up at constant specific power is even much more safer and as it follows from Eq. (6b) at $c_v > 0.25$ the scale-up at constant tip speed ($n \sim d^{-1}$) is on the safe side.

5. Nomenclature

b	coefficient in Eq. (2)
c, C	coefficients in Eq. (1)
c_m	mass particle concentration (kg/m^3)
c_v	volumetric particle concentration
d	impeller diameter (m)
d_p	particle diameter (m)
D	vessel diameter (m)
Fr′	modified Froude number, $\mathrm{Fr}' = n^2 d\rho / g\Delta\rho$
Fr'_0	coefficient in Eq. (2) having a physical meaning of the value Fr′ for $c_v \to 0$
g	acceleration due to gravity (m/s^2)
n	agitator speed (s^{-1})
w	baffle width (m)
ρ	liquid density (kg/m^3)
$\Delta\rho$	solid–liquid density difference (kg/m^3)

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