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Mixing of fine suspensions – effect of particle concentration

Introduction

As it was shown in [1] the agitator speed necessary for mixing of fine particle suspensions cannot be calculated from relations recommended for suspensions of greater particles. Flow properties of such suspensions change from Newtonian at low particle concentrations to non-Newtonian at high concentrations of solids in suspension. This must be taken into account during a design of mixing equipment. In the paper, the effect of particle concentration on impeller speed necessary for mixing suspension is presented.

Theoretical background

In order to design mixing apparatuses it is important to ensure flow in the whole vessel volume The results of critical (just-suspended) impeller speed for off-bottom particle suspension with the given solid phase concentration c_v and mixing equipment geometry can be correlated in the power form

$$Fr' = C\left(\frac{d_p}{D}\right) \tag{1}$$

The values of coefficients C and c depend on particle volumetric concentration c_v and the graphical form of these dependences are presented in [1]. The concentrated fine suspensions exhibit non-Newtonian behaviour and the critical point for suspension mixing transfers from vessel bottom to the batch surface. Rheological behavior of such suspensions can be usually described by *Bingham* model

$$\tau = \tau_0 + \mu_p \gamma \tag{2}$$

As it was shown in [2] the dimensions of mixed cavern around rotating impeller are determined by the criterion $n^2d^2\rho/\tau_0$, which is proportional to the ratio of dynamic pressure to yield stress τ_0. At highly concentrated and viscous suspensions also viscous stress can influence the mixing process. The ratio of dynamic pressure to viscous stress (or inertial forces to viscous forces) is proportional to plastic *Reynolds* number

$$Re_p = \frac{nd^2\rho}{\mu_p} \tag{3}$$

To eliminate the agitator speed from dimensionless criteria, their combination

$$He = Re_p^2 \frac{\tau_0}{n^2 d^2 \rho} = \frac{\tau_0 d^2 \rho}{\mu_p^2} \tag{4}$$

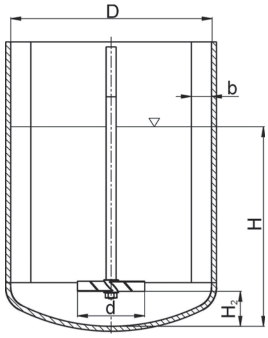
called the *Hedstrőm* number is often used.

For comparison of power consumption needed for mixing in different mixing equipment with given vessel diameter the following new dimensionless criterion was proposed

$$\frac{P^2\rho}{\tau_0^3 D^4} = \left(\frac{n^2 d^2 \rho}{\tau_0}\right)^3 Po^2 \left(\frac{d}{D}\right)^4 \tag{5}$$

Experimental

The pitched six blade turbines were used in model measurements. The ratio of vessel to impeller diameter D/d was 3. The measurements were carried out in dish-bottomed vessels with diameter 200 and 300 mm. The height of impeller above the vessel bottom was equal to $0.75d$. The impeller has been operated to pump the liquid downwards the vessel bottom. The vessels were equipped with four radial baffles of width $b = 0.1D$. The height of the liquid level was equal to the vessel diameter $H = D$. The experimental layout is shown in Fig. 1.



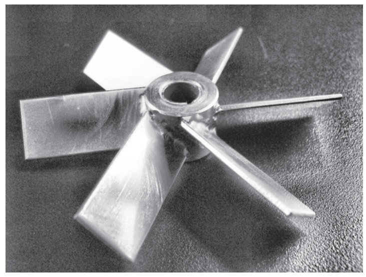


Fig. 1. Experimental layout with pitched six blade impeller

The water suspensions of chalk were used in measurements. The chalk particles have mean volumetric diameter 4.6 μm, their volumetric concentration changed in the range from 0.025 to 0.4.

There was dissolved 5% b.w. of NaCl in the liquid phase of the suspension, tanks to which electrochemical method, described e.g. in [3], could be used for measurements of just suspended impeller speed at the vessel bottom. However, the presence of salt had also effect on rheological properties of the suspensions as it was shown in [4]. The dependencies of shear stress on shear rate for suspensions with particle content in the range from 0.25 to 0.4 are depicted on Fig. 2.

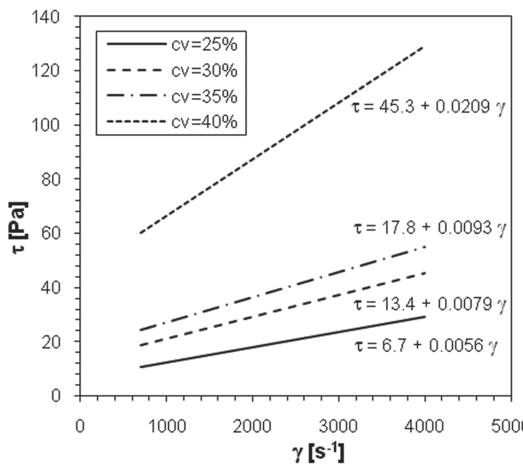


Fig. 2. Rheograms of chalk suspensions

The electrochemical method was used for measurements of the impeller speeds necessary for mixing in low-concentrated suspension only (up to 20%). The measurements were checked also visually. Only just suspended state at the vessel bottom was observed at the measurements. At higher concentrations (above 20%) all visible regions of suspension in the vessel were observed and the critical speeds for mixing were determined as the speed at which the suspension moved sufficiently in the whole volume (e.g. at the vessel bottom, at the wall, and at the liquid level). The sufficiency of the movement was defined as a state in which the flow of particles was observable during a short time period (approx. 2 s) at all mentioned places.

Experimental results

The modified Froude number values calculated from equation (1) for fine chalk suspensions were compared with experimental results as it is shown in Fig. 3. The relatively good agreement of experimental with calculated values were found at low particle contents only. At higher concentrations of particles the equation (1) does not give correct results.

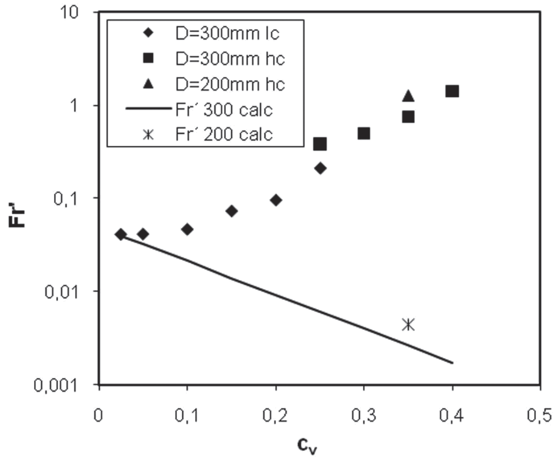


Fig. 3. Comparison of calculated and experimental values of modified *Froude* number at different particle content

As it was stated above, the concentrated fine suspensions exhibit non-Newtonian behaviour and the critical point for suspension mixing transfers from vessel bottom to the batch surface. This is presented in Fig. 3 by the two points at particle content 0.25. The lower placed point is given at impeller speed corresponding to just suspended state at the vessel bottom. However the critical point of suspension mixing was not at the bottom but at the level surface and the corresponding modified Froude number calculated from critical impeller speed obtained from measurement at this place is presented by the upper placed point. In the figure, there are also depicted two points obtained from measurements at smaller vessel (D = 200 mm for experimental value and Fr'200 calc for calculated value).

To see the influence of viscous forces on impeller speed necessary for sufficient movement during mixing of highly concentrated suspensions (above 25%), the dependence of criterion $n^2d^2\rho/\tau_0$ on *Hedström* number was created (Fig. 4). The results presented in this figure can be characterized by the mean value of $n^2d^2\rho/\tau_0$ = 97.5 and it can be said that the viscous forces have practically no influence on the value of just suspended impeller speed.

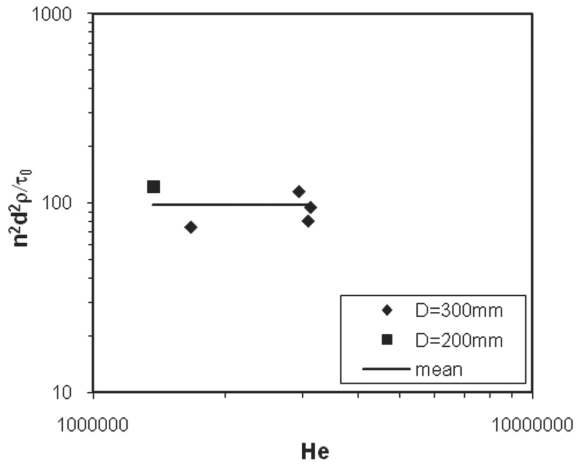


Fig. 4. Dependence of ratio $n^2d^2\rho/\tau_0$ on *Hedström* number *He* for measurements with pitched six-blade impeller of diameter $d = D/3$.

The same dependence for six pitched blade turbine with $D/d = 2$ calculated from results presented in [4] is shown in Fig. 5. The results presented in this figure can be characterized by the mean value of $n^2d^2\rho/\tau_0$ = 38.1.

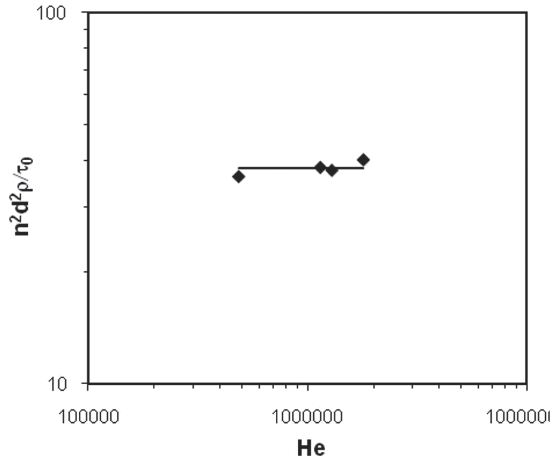


Fig. 5. Dependence of ratio $n^2d^2\rho/\tau_0$ on *Hedström* number *He* for measurements with pitched six blade impeller of diameter $d = D/2$

Conclusions

From the results it can be seen that impeller speed necessary for mixing of highly concentrated fine suspension cannot be easily calculated from suspension characteristic of the pitched six-blade impeller presented in [1]. For determination of the speed the suspension movement in whole batch must be observed.

The value of $P^2\rho/(\tau_0^3D^4)$ = 35 043 was calculated for turbine with ratio $D/d = 3$, the corresponding value for turbine with $D/d = 2$ was 12 976. Comparing both values, the advantage of greater impellers for mixing of concentrated fine suspensions is obvious. This corresponds with results presented in [5].

Symbols

- c_v – volumetric concentration of particles, [-]
- c – exponent in Eq. (1), [-]
- C – coefficient in Eq. (1), [-]
- d – agitator diameter, [m]
- d_p – particle diameter, [m]
- D – vessel diameter, [m]
- Fr' – modified *Froude* number, $Fr' = n_c^2 d\rho_l/(g\Delta\rho)$, [-]
- g – gravity acceleration, [m·s^{-2}]
- He – *Hedström* number, eq. (4), [-]
- n – agitator speed, [s^{-1}]
- P – power consumption, [W]
- Po – power number, [-]
- Re_p – plastic *Reynolds* number, eq. (3), [-]
- γ – shear rate, [s^{-1}]
- μ_p – plastic viscosity, [Pa·s]
- ρ – suspension density, [kg·m^{-3}]
- ρ_l – liquid density, [kg·m^{-3}]
- $\Delta\rho$ – solid-liquid density difference, [kg·m^{-3}]
- τ – shear stress, [Pa]
- τ_0 – yield stress, [Pa]

LITERATURE

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