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Dense Solid-Liquid Suspensions in Top-Covered Unbaffled Stirred Vessels

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In the present work solids suspension is investigated in an unbaffled tank stirred by a Rushton turbine and provided with a top-cover in order to avoid the formation of the well known central vortex. The data obtained are compared with those pertaining baffled stirred tanks *via* comparison with the well known Zwietering's correlation. The dependence of N_{js} on particle concentration is found to be similar to that well established for baffled vessels, while, as a difference from the latter, N_{js} is found to decrease when liquid viscosity increases. Results also show that N_{js} is substantially independent of particle size, a feature that may advice the adoption of unbaffled tanks when large heavy particles are to be dealt with. On the other hand, a smaller exponent for the scale-up rule is found with respect to baffled tanks, which implies the need for larger specific power consumptions the larger the vessel size and may limit useful applications to small to medium plant sizes. Finally, a correlation akin to Zwietering's correlation is proposed for top-covered unbaffled stirred tanks.

1. Introduction

An important parameter for the design of solid-liquid stirred tanks is represented by N_{js} i.e. the minimum agitation speed necessary to suspend all the particles in a stirred tank. A lot of efforts have been devoted so far to the assessment of this parameter (Zwietering, 1958; Nienow, 1968) by visual observations as well as by alternative procedures. Almost all these studies dealt with stirred tanks provided of baffles aimed at breaking the undesired tangential components of velocity and consequently avoiding the central vortex formation at high impeller speeds.

Although baffled tanks are widely used for better mixing of liquids or of solid particles and liquid, there are some specific applications where the presence of baffles may be undesirable: among the others crystallization, precipitation processes, mixing within viscous fluids, biological and pharmaceutical processes. Scientific literature emphasizes a continuous increasing interest towards unbaffled stirred vessels: both experimental (Tezura et al., 2007; Tamburini et al., 2009; Brucato et al., 2010) and computational studies (Derksen, 2006; Sbrizzai et al., 2006) have been carried out, often showing good perspectives for a massive use of such systems.

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2. Experimental information and *SCRM* fundamentals

The experimental system consisted of a cylindrical flat bottomed baffled tank with vessel diameter (T) and total liquid height (H) equal to 0.19m. A standard six-bladed Rushton turbine with D=T/2 was used in the suspension experiments. It was set at a distance from vessel bottom equal to 1/3 H. The seal between the cover and the vessel was guaranteed by an o-ring gasket. A bigger unbaffled tank was used to investigate scale-up effects. This bigger tank was geometrically similar to the former and had a diameter T=0.48m.

Particle suspension was assessed by the "Steady Cone Radius Method" (SCRM), a technique recently introduced. In particular a digital photo-camera was placed below vessel bottom for image acquisition (for both tanks). An exposure time equal to one second was set in accordance to Zwietering's *one second* criterion (Zwietering, 1958). About twenty images per agitation speed N were collected and successively analyzed. With this technique at agitation speeds $N<N_{js}$ the recorded images show a circle (placed at the tank bottom centre) of motionless particles which are well focalized, conversely, suspended particles appear blurred. Increasing N, the radius of this circle decreases as more particles are suspended; the impeller speed at which this radius gets the zero value is considered to be N_{js}. Full details on *SCRM* apparatus and fundamentals can be found in Brucato et al. (2010).

Silica particles and pure deionised water or silica particles and water-glycerol solutions were employed during experiments. Different solid loadings were used to assess the dependence of N_{js} on particle concentration B. Independence of N_{js} on particle diameter d_p was investigated by utilizing 250-300µm, 600-710µm as well as un-sieved particles.

Different ratios of water and glycerol were used to prepare solutions of different cinematic viscosity ν. Standard Ubbelohde viscometers were employed to measure the viscosity of these solutions.

3. Results and discussion

All the results concerning N_{js} which are presented throughout this section are compared with corresponding N_{js} values obtained on the basis of the well known Zwietering's correlation for standard baffled vessels. The dimensionless constant S of Zwietering's correlation was considered equal to 5.2 in accordance to literature (Nienow, 1968).

Brucato et al. (2010) found that N_{js} is practically not dependent on particle diameter for unbaffled vessels provided with a top-cover. Present results confirm this important result, as it can be seen in Fig.1a. First of all, N_{js} was assessed for the cases of 275 µm and 655 µm at different particle concentrations and no differences (at a given solid loading) were found. Mixture of these two particle types provided the same results as well. Analogous experiments were carried out by employing un-sieved particles whose particle size distribution cumulative curve is plotted in Fig.1b. At B=2.5% and B= 5% identical N_{js} values were obtained while at B=10% a lower N_{js} was found. This finding is allegedly due to the lower voidage of the particle bed: this leads to a reduction of the flow able to cross the bed and the lateral thrust undergone by the sediment increases consequently. At N_{js} the sediment shows a rigid motion where interstitial liquid is scarcely replaced, thus suggesting that *SCRM* may be misleading in this case.

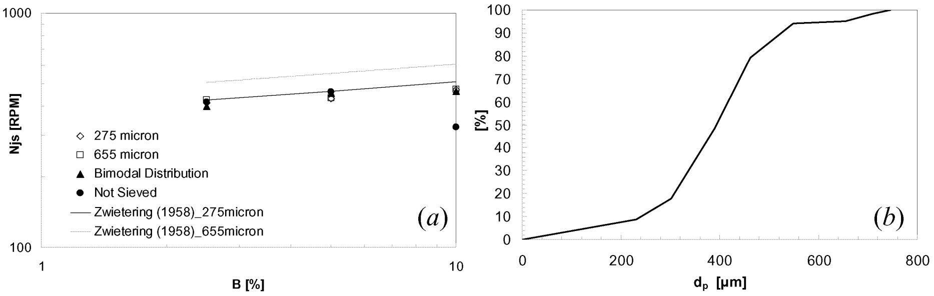


Figure 1: (a) dependence of N_{js} on particle diameter and solid concentration; (b) particle size distribution cumulative curve for the case of not sieved particles.

Observing both Fig.1a and Fig.2 it appears that the dependence of N_{js} on solid concentration is very similar to that predicted by Zwietering (1958), i.e. $N_{js} \propto B^{0.13}$, in agreement with previous findings (Brucato et al. ,2010).

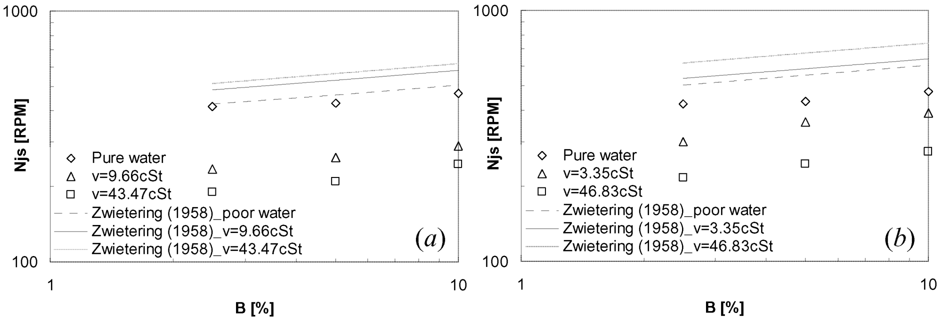


Figure 2: Dependence of N_{js} on kinematic viscosity and particle concentration. (a) 250-300μm; (b) 600-710μm.

As far as N_{js} dependence on kinematic viscosity is concerned, Fig.2 shows that an increase in kinematic viscosity leads to a large decrease of N_{js} (for both particle diameters).

This behaviour marks an important difference between unbaffled and baffled tanks (Fig.3) as in baffled vessels N_{js} increases with the kinematic viscosity according with Zwietering's correlation.

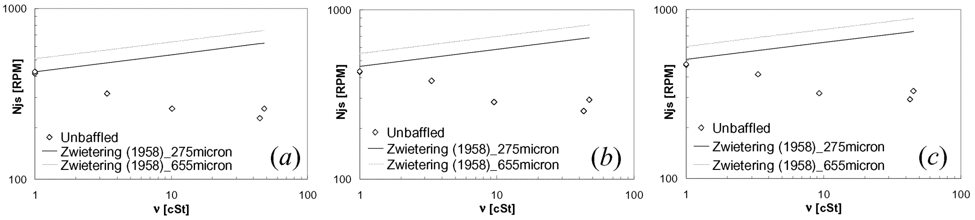


Figure 3: Dependence of N_{js} on kinematic viscosity. (a) B=2.5%; (b) B=5%; (c) B=10%.

Actually, a globally accepted dependence of N_{js} on ν does not exist for baffled vessels as some authors disagree with the dependence predicted by Zwietering. Tezura et al. (2007) carried out N_{js} assessments in unbaffled vessels stirred by unsteadily radial impellers and they found that this parameter does not depend on the kinematic viscosity. This difference between Zwietering (1958), Tezura et al. (2007) and the present work is likely linked to the different suspension mechanisms involved. For baffled and unsteadily stirred unbaffled vessels the suspension phenomenon is linked to velocity turbulence fluctuations near the tank bottom, while for the present case of top-covered unbaffled vessels it is due to fluid mean velocities. Clearly, an increased fluid viscosity damps turbulent fluctuations as well as enhances the drag coefficient thus resulting in different dependence of N_{js} on viscosity for the two suspension mechanisms.

Fig.3 shows that the larger the kinematic viscosity, the higher the difference between N_{js} values for Zwietering-baffled and top-covered unbaffled vessels at each solid loading. Notably, in relation to the independence of N_{js} on particle diameter, results relevant to different particle diameters are plotted indistinctly in each graph of Fig.3. By fitting the experimental data of each graph by a power law and by averaging the relevant exponents the following dependence was found: $N_{js} \propto \nu^{-0.13}$.

Most data points obtained in the top-covered unbaffled tank are below Zwietering's correlation lines especially when big particles and/or solutions with high kinematic viscosities are employed.

Some experiments with the larger tank (T=0.48m) were performed and the relevant results are reported in Fig.4. These experiments confirmed the independence of N_{js} on particle diameter as well as its dependence on particle concentration (similar to that predicted by Zwietering). Conversely, dependence of N_{js} on factor scale D was found different than that of baffled vessels: Zwietering found that $N_{js} \propto D^{-0.85}$ while experiments performed in the present top-covered unbaffled vessel showed that $N_{js} \propto D^{-0.5}$. The scale factor exponent 0.5 is lower than 2/3 thus resulting in an increase of power input per unit volume with an increase of the scale factor. Conversely, in accordance with Zwietering's correlation, an increase of the scale produces a reduction of power per unit volume.

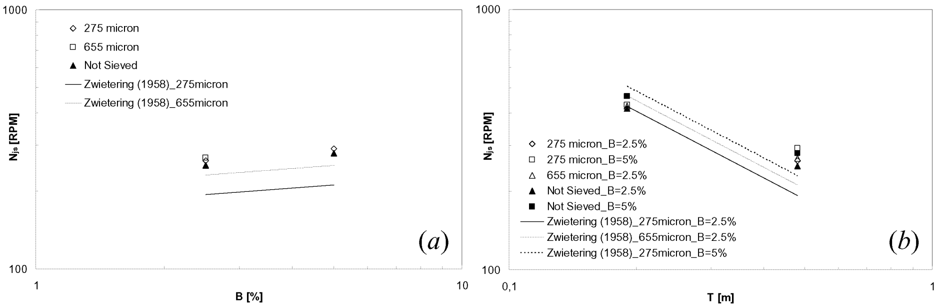
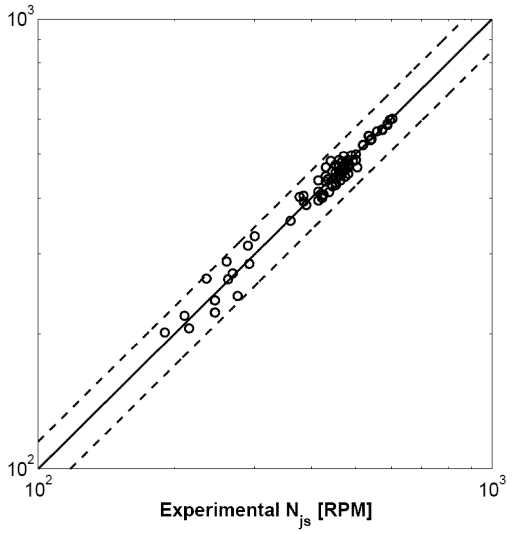


Figure 4: Scale-up effects. (a) dependence of N_{js} on particle concentration and diameter; (b) dependence of N_{js} on the vessel diameter (small scale T=0.19m, large scale T=0.48m).

Eventually, a correlation for the prediction of N_{js} in unbaffled vessels provided of a top-cover was devised in accordance with the mathematical form of Zwietering's correlation (1958). This was obtained by carrying out a multiple regression of all presently collected data and previously available data (Brucato et al., 2010) resulting in the exponents showed in the following equation:

$$N_{js} = \frac{9.85 \cdot d_p^{0.0352} \cdot \left(\dfrac{g\Delta\rho}{\rho}\right)^{0.3315} \cdot B^{0.1133}}{\nu^{0.142} \cdot D^{0.4344}} \tag{1}$$

Experimental N_{js} values were compared with corresponding N_{js} values calculated by means of the equation 1: the comparison is depicted in Fig.5.



The upper and the lower broken lines indicate errors of +15% and -15% respectively as regards the exact prediction of each experimental value of N_{js}. Fig.5 shows the good reliability of the proposed correlation since all prediction errors are lower than 15%.

Figure 5: Experimental N_{js} versus N_{js} calculated by equation 1.

4. Conclusions

In the present work N_{js} values of several solid-liquid suspensions in a radially stirred top-covered unbaffled tank were assessed by means of the *Steady Cone Radius Method* devised by Brucato et al. (2010). Dependences of N_{js} on particle diameter and concentration, liquid viscosity and system scale were investigated.

Results confirm the negligible dependence of N_{js} on particle diameter as well as the dependence of N_{js} on solid loading found by Zwietering (1958) for baffled vessels and Brucato et al. (2010) for top-covered unbaffled vessels.

As a difference from baffled tanks and unsteadily stirred unbaffled vessels (Tezura et al., 2007), N_{js} was found to decrease with an increase in liquid kinematic viscosity.

As far as scale-up effects are concerned, N_{js} dependence on the scale factor was lower than that predicted by Zwietering for baffled vessels. Notwithstanding top-covered unbaffled vessel P_{js} (power requirements at N_{js}) values were found to be much smaller (by about one order of magnitude) than the relevant values in baffled systems (Brucato et al., 2010), the scale up criterion of power per unit volume showed an increase of specific power requirements with the system scale for the present case of top-covered unbaffled vessels. This finding suggests an economic convenience for radially stirred top-covered unbaffled vessels only under a certain scale.

Finally, a quite effective Zwietering-like correlation for the prediction of N_{js} in top-covered unbaffled vessels was devised by employing all the data collected by Brucato et al. (2010) and within the present work.

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