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Comparison of Agitators Performance for Particle Suspension in Top-Covered Unbaffled Vessels

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Power savings is a problem of crucial importance nowadays. In process industry, suspension of solid particles into liquids is usually obtained by employing stirred tanks, which often are very power demanding. Notwithstanding tanks provided with baffles are traditionally adopted for this task, recent studies have shown that power reductions can be obtained in top-covered unbaffled vessels. In the present work experiments were carried out in a top-covered unbaffled vessel with a diameter T=0.19m and filled with distilled water and silica particles. Two different turbines were tested: a standard six-bladed Rushton Turbine (RT) and a 45° four bladed Pitched Blade Turbine (PBT). For the case of the PBT both the up-pumping (PBT-Up) and the down-pumping (PBT-Down) operation mode were tested. Two different impeller sizes D (T/3 and T/2) and clearances C (T/3 and T/10) were investigated. The effects of particle size and concentration were also assessed. Investigations concern the assessment of the minimum impeller speed for complete suspension (N_{js}) along with the measurement of the relevant power consumption (P_{js}) aiming at identifying the most efficient tank-turbine configuration among those investigated here. Results were also compared with corresponding ones pertaining to baffled tanks (obtained via correlations available in the literature). Results have shown that the RT with D=T/3 and C=T/3 and the PBT-Up with D=T/2 and C=T/10 appear to be the most convenient (least power demanding) options. Finally, a significant power saving with respect to the most efficient baffled configurations was observed thus confirming the convenience of operating solid-liquid suspensions in an unbaffled system for all those processes where the mixing time is not a limiting factor.

1. Introduction

Mixing of solid particles into liquids is usually carried out in stirred tanks. Such operation is traditionally performed in tanks provided with baffles, although in recent years the scientific interest is moving also towards unbaffled vessels. Busciglio et al. (2014) assessed the mixing times in uncovered unbaffled tanks via an image analysis technique. They confirm that unbaffled vessels are poorer mixers than baffled ones, although comparable mixing efficiencies can be found when the free surface vortex bottom approaches the impeller plane. Scargiali et al. (2014) investigated the mass transfer capability of a free surface (i.e. uncovered) unbaffled tank: experimental results showed that this kind of bioreactor can provide sufficient oxygen mass transfer for animal cell growth, thus resulting in a viable alternative to the more common baffled sparged reactors. Montante and Paglianti (2014) investigated the hydrodynamic characteristics of a model unbaffled bioreactor via Particle Image Velocimetry (PIV). Scargiali et al. (2013) studied the influence of the Reynolds and Froude numbers on the power consumption characteristics in unbaffled stirred tanks operating both in non-aerated conditions (subcritical regime) and in aerated conditions (supercritical regime), i.e. when the free surface vortex has reached the impeller and the gas phase is ingested and dispersed inside the reactor. Authors proposed an overall correlation for power number prediction, able to deal with both the subcritical and supercritical regimes. Tamburini et al. (2009 and 2013) presented a novel non-intrusive technique (named laser sheet-image analysis technique) and employed it to study the particle distribution in a dilute solid-liquid suspension within a top-covered unbaffled system. They found that the solid particles prefer to accumulate

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within two toroidal attractors placed upon and below the impeller respectively. Moreover the higher the particle inertia, the higher the particle concentration within the two tori.

Particularly, many research efforts have been recently devoted to the assessment of the most efficient conditions for solid-liquid suspension mixing within both top-covered and free surface unbaffled stirred reactors. Tamburini et al. 2012a measured the power requirements needed to achieve complete suspension conditions in a free surface unbaffled system. For a similar system Wang et al. (2014) investigated particle suspension in high-concentration slurries. They found that the specific power requirements (based on the mass of solids) for complete suspension can be minimized by operating the system at relatively higher solids concentrations in the range of 0.20−0.35 (volume/volume) and by using higher-power-number impellers under unbaffled conditions over a range of solids concentrations. Brucato et al. (2010) and Tamburini et al. (2011) investigated the effect of different parameters (particle diameter, concentration and density, liquid viscosity) on N_{js} for the case of a top-covered unbaffled tank stirred by a Rushton turbine. Aim of this work is to move forward by enlarging the number of turbine-tank geometrical configurations investigated and focusing on the estimation of P_{js}. The present work is devoted to find the optimal geometrical configuration (impeller type, diameter and clearance) able to provide the lowest value of P_{js} for the case of a top-covered unbaffled stirred tank.

2. Experimental

The experimental campaign was carried out on a transparent (Plexiglas®) unbaffled tank with a diameter T=0.19m and a height H=T. The tank was provided with a top-cover and completely filled with distilled water to avoid the typical air vortex formation. A sketch of the system can be found in Tamburini et al. (2014b).Two different turbines were tested: a standard six-bladed Rushton Turbine and a 45° four bladed PBT. The latter was operated either in the PBT-Up or on the PBT-Down operation mode. For each impeller two different diameters D were employed: the one equal to T/3, the other equal to T/2. Also, two different turbine-offsets from vessel bottom were investigated: either C=T/3 or C=T/10. As it concerns the solid-phase, silica particles were employed (density = 2.480 kg/m^3) and the effects of particle size and concentration were assessed. In particular, two different particle size were investigated: either d_p=250-300μm or d_p=600-710μm. Finally, four different solid loadings B% were tested: 2.5, 5, 10 and 20 solids-weight/liquid-weight %.

2.1 N_{js} assessment

In order to compare the mixing efficiency for complete suspension of the turbines tested, it is preliminarily necessary to assess N_{js}. Assessment was performed via a direct method (Tamburini et al., 2012b) consisting in the camera assisted application of the visual one second criterion by Zwietering (1958). Practically, a camera was placed underneath vessel bottom and a number of images (about 20) were collected at each impeller speed. Camera exposure time was set to one second in accordance with Zwietering's criterion, so that motionless particles appeared to be well defined, while moving particle images were blurred in the pictures. N_{js} was defined as the minimum impeller speed at which all particles appear blurred in all pictures. Clearly, the employment of camera and collected images strongly reduces the subjectivity of the visual application of Zwietering's criterion. Full details on this methodology can be found in Tamburini et al. (2014a). Notably, according to the assessment procedure, the N_{js} values refer to the achievement of "on-bottom" complete suspension (Tamburini et al., 2014a).

2.2 P_{js} measurement

Once N_{js} values were collected, corresponding P_{js} were measured. Power measurements were carried out by measuring the torque which is transmitted from the turbine to the tank through the fluid. The apparatus employed for this measurement is a "static-frictionless" turntable consisting of a granite dish able to rotate around its central axis on a granite table. It is described in detail in Brucato et al. (2010).

A sketch this experimental apparatus is reported in Tamburini et al. (2014a).

3. Results and Discussion

As a first step, the values of N_{js} were measured for each single configuration (turbine type, diameter and clearance, particle diameter and concentration). Relevant results are not reported in the following for the sake of brevity. The knowledge of the minimum speed for complete suspension is an essential preliminary operation necessary to measure the relevant power requirements P_{js}, which is the parameter to use for the turbine performance comparison. All collected P_{js} data are also compared with corresponding values relevant to baffled vessels. The latter were assessed via correlations available in the literature and power number data (N_p) purposely collected under turbulent conditions in a corresponding baffled vessel. For RT the assessed N_p values are N_p = 4.9 for the configuration D = T/3, C = T/3; N_p = 4.8 for D = T/2, C = T/3; N_p = 3.7 for D = T/3, C

= T/10; N_p = 3.5 for D = T/2, C = T/10. For the PBT-Down: N_p = 1.5 for the configuration D = T/3, C = T/3; N_p = 1.4 for D = T/3, C = T/10. For the PBT-Up no measurement was carried out: the N_p values at C=T/3 were estimated to be 33% higher than those relevant to the corresponding PBT-Down in accordance with Aubin et al. (2001). No estimation was performed for the low-clearance case. Notably, (i) no correlation was found for the PBT-Down with D=T/2 and (ii) the N_{js} relevant to the PBT-Down with D=T/3 and C=T/10 were extrapolated slightly beyond the range employed for the proposition of the correlation (Wong et al., 1987).

3.1 Rushton Turbine

In Figure 1 the P_{js} as a function of the solid concentration results are shown: these are relevant to the different configuration of the Rushton turbine. On the left the results refer to the smaller particle size, while on the right refer to the higher particle size. As it can be seen, the lowest P_{js} values were found for the RT with D=T/3 and C=T/3. Conversely, the larger impeller at the same clearance (RT with D=T/2 and C=T/3) exhibited the highest P_{js} values (i.e. the least efficient configuration). The same hierarchy was found for the larger particle size. The dependence of P_{js} on particle concentration was found to be similar for all the configurations and also similar to that pertaining baffled tanks (i.e. proportional to $B^{0.13}$ as proposed by Zwietering). Regarding the dependence on particle size, it appears to be quite small as already reported in the literature (Tamburini et al., 2014a). Also, it is quite smaller than that exhibited by the baffled configurations thus suggesting an additional convenience of adopting unbaffled tanks for the suspension of larger particles. Moreover, as a difference from the baffled configuration, the passage from double (C=T/3) to single (C=T/10) loop configuration does not always produce a reduction of P_{js}: there is a reduction for the larger impeller and an increase for the smaller one. This is probably due to the particular flow pattern of an unbaffled system where the motion is dominated by the azimuthal velocity rather than by recirculation loops. More interestingly, all the P_{js} values relevant to the unbaffled system are significantly lower than those relevant to the baffled tanks. Notably, the data inferred via the Zwietering correlation refer to the C=T/3 configurations, while the data inferred via the Armenante et al. (1998) correlation refer to the low clearance impellers (C=T/10).

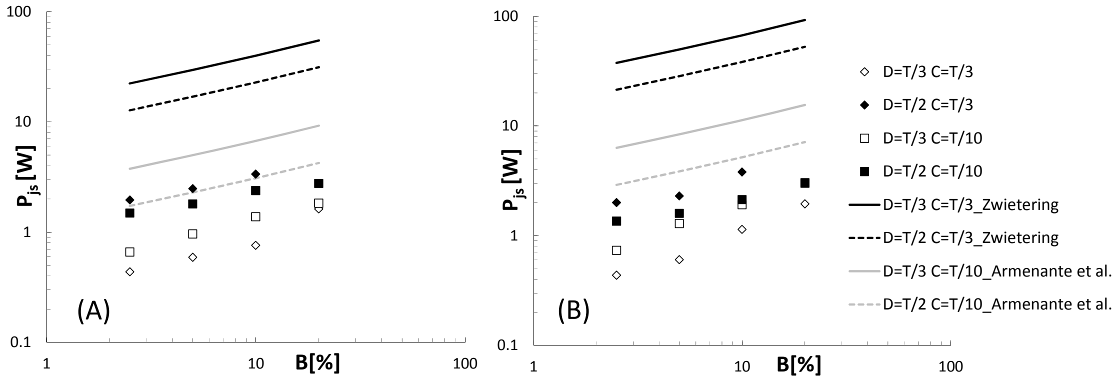

Figure 1: P_{js} vs B for the case of the Rushton turbine: (A) d_p=250-500μm; (B) d_p=600-710μm.

3.2 Pitched Blade Turbine

3.2.1 Down Pumping

Figure 2 reports the dependence of P_{js} on the solid concentration B% for each PBT-Down configuration. In this case it is not easy to find the most efficient configuration for any solid loading and particle size, because of the singular behaviour exhibited by this turbine: in some cases even a reduction of P_{js} with B% was observed for the larger turbine. This occurs since, in some cases, as the solid concentration increases, particles constitute stable agglomerates, which start moving as a whole rolling on the bottom. Such occurrence, along with the definition of complete on-bottom suspension employed (for N_{js} assessment), may result into N_{js} values, which do not increase or even decrease as the solid loading increases. Larger particles do not exhibit the same singular behaviour. However, the large PBT-Down placed at C=T/3 seems to be the best compromise among the configurations tested. As a difference from the RT case, here there is a more marked dependence of P_{js} on d_p, especially at the higher concentrations. The values relevant to the baffled vessels (Wong et al., 1987) are more than one order of magnitude higher than the corresponding ones in the unbaffled system when the turbine is placed at C=T/3, while a less different efficiency was found for the low-clearance configurations.

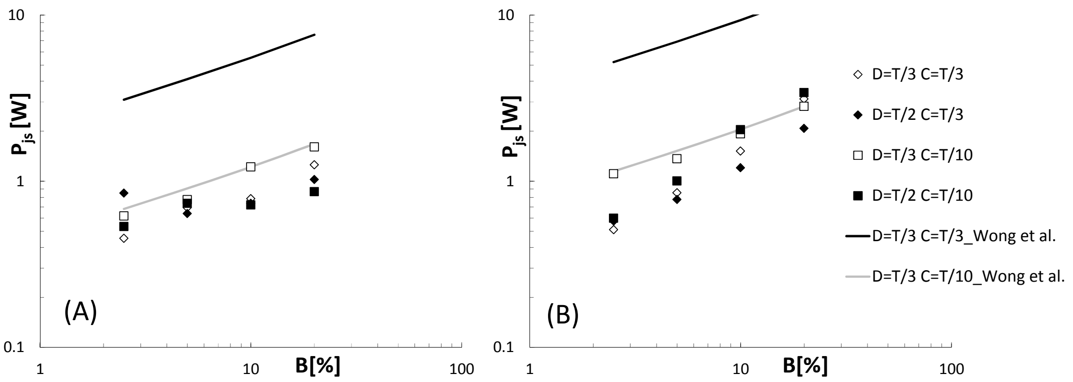

Figure 2: P_{js} vs B for the case of the PBT-Down: (A) d_p=250-500μm; (B) d_p=600-710μm.

3.2.2 Up Pumping

Even when the operation mode of the turbine is changed, the larger PBT-Up with the small particle size exhibits a non-monotonic dependence of P_{js} on B% (Figure 1A). Also, the same larger turbine exhibits in some conditions a counter intuitive dependence on particle size. These unusual occurrences might allow easier operation at high solids concentrations and high particle size. For all other cases, the dependence of P_{js} on B% appears to be quite similar to those of the baffled tanks. For both the particle size, Figure 3 shows that the PBT-Up with D=T/2 and C=T/10 provides the lowest power requirements for most of the conditions tested. On the other hand, the small turbine placed at the same clearance is the worst option. As concerns the comparison with the baffled configurations (Myers and Bakker, 1998), the suspension efficiency of the unbaffled tanks is largely higher: P_{js} values in the unbaffled tank are more than one order of magnitude lower than baffled tanks.

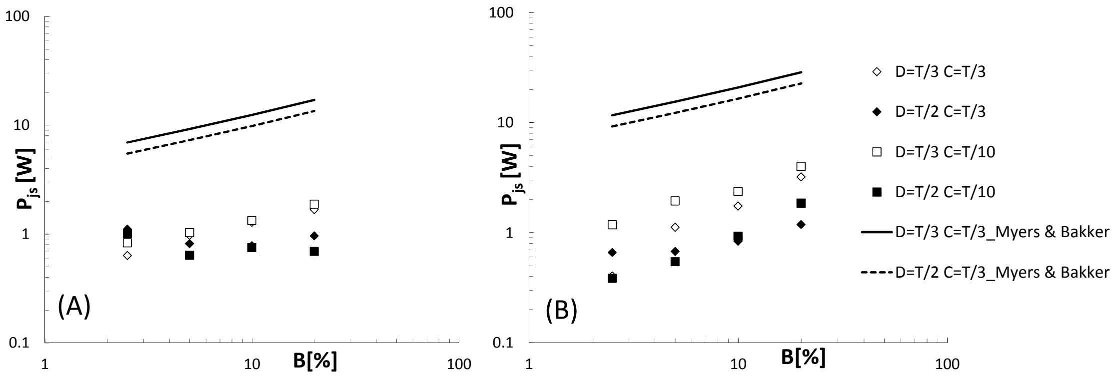

Figure 3: P_{js} vs B for the case of the PBT-Up: (A) d_p=250-500μm; (B) d_p=600-710μm.

3.2.3 PBT operation mode comparison

In Figure 4 the comparison of the operation mode performance of each PBT configuration is reported. For the case of the smaller turbine configurations, the down pumping operation provides better performance as expected. Conversely, the particular dependence of P_{js} on particle concentration and size exhibited by the larger turbine results into a more complex situation: for the case of the highest solids loading and particle size, the down pumping operation mode is the worst option, while there are some conditions where the up-pumping mode results into a better performance. Practically, for the larger PBT, it is not possible to identify a configuration mode providing the lowest P_{js} values at any conditions.

3.3 Comparison

In this final section all the results reported so far are compared to find the best configuration. In particular, Figure 5 shows only the most efficient configuration among those presented in the previous sections. Moreover, these results are compared with literature data concerning the most efficient configurations (obtainable with the high efficiency Lightnin® impeller A310) for solids suspension in baffled stirred tanks. Literature data concerning N_{js} were inferred from data by Wong et al. (1987) and Ibrahim and Nienow (1996): note that for the case of the low-clearance configurations data were extrapolated slightly outside the range employed for the proposition of the correlation.

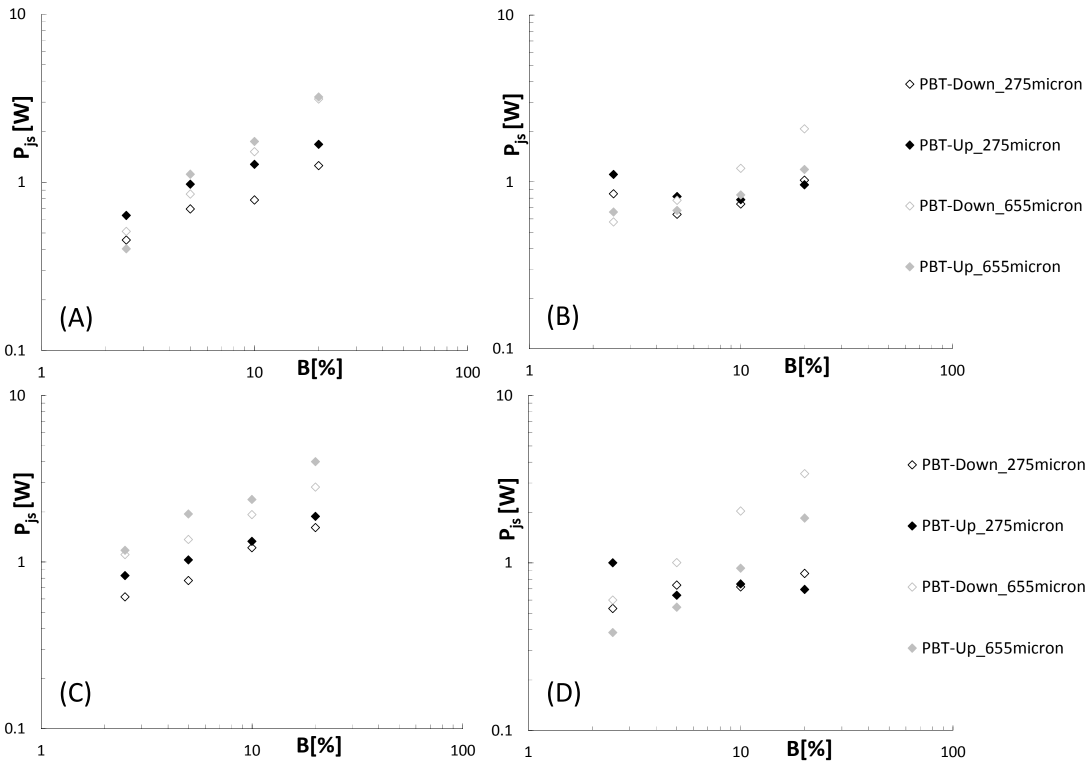

Figure 4: P_{js} vs B: Comparison between the PBTs. (A) D=T/3 C=T/3; (B) D=T/2 C=T/3; (C) D=T/3 C=T/10; (D) D=T/2 C=T/10.

As concerns the A310 N_p values, these were purposely measured resulting into 0.36 for D=T/3 and C=T/3, 0.33 for D=0.45T and C=T/3, 0.35 for D=T/3 and C=T/10, 0.36 for D=0.45T and C=T/10. As it can be seen, it is not possible to find a configuration, which provides the lowest power requirements for complete suspension at any condition: for instance the use of the PBT-Down with D=T/3 and C=T/3 provides good performance for the lowest d_p (Figure 5A), while it is inconvenient for the larger particles (Figure 5B).

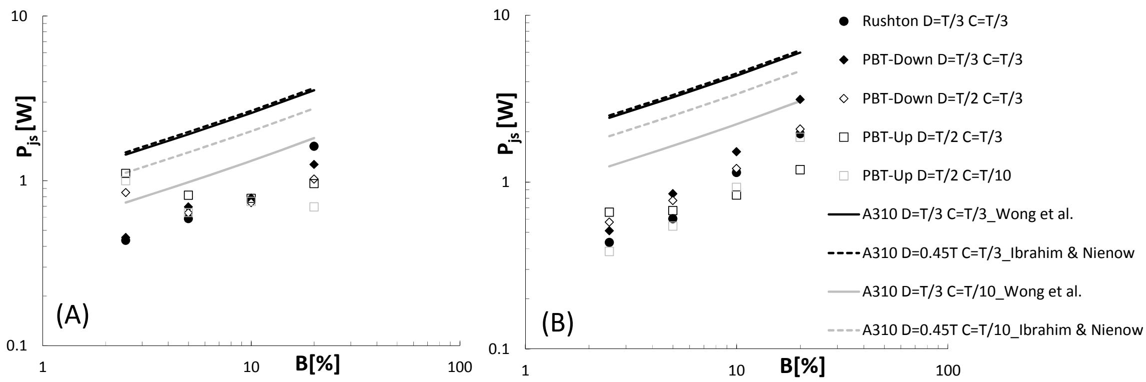

Figure 5: P_{js} vs B: Comparison between the most efficient stirrers: (A) d_p=250-500μm; (B) d_p=600-710μm.

Similar considerations can be done also for the PBT-Down with D=T/2 and C=T/3. As concerning the most efficient up pumping PBT, the one with C=T/3 appears to be unsuitable at the lower concentration, while it performs better at larger B%. The low-clearance one provides the lowest P_{js} values for the larger particles and at the intermediate-to-low solids concentration. Finally, the RT reported in Figure 5 seems to be a good compromise and in particular it is more suitable at intermediate-to-low solids loadings. More interestingly, none of the most efficient baffled configurations provides suspension efficiency better than those pertinent to the unbaffled tanks. This gap is more evident when largest particles are employed.

4. Conclusions

An unbaffled mechanically stirred tank filled with mono-dispersed silica particles suspended in water was studied. N_{js} and P_{js} were measured for several different geometrical configurations (impeller type, impeller diameter, impeller clearance) and different system physical properties (particle size and concentration). Results were compared with corresponding P_{js} values relevant to identical tanks provided with baffles. A geometrical configuration being the most power efficient at any condition was not found. However, on the basis of the data collected, the Rushton Turbine with D=T/3 and C=T/3 and the low clearance PBT-Up with D=T/2 seems to be a good compromise for all the conditions tested in the present work. Finally, it is worth noting that at present these configurations should be regarded as the best-choice standard for solids suspension, at least at the system scale investigated in the present work and for all those systems where mixing time is not the controlling factor.

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