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The Effect of Flow Reversal on Solids Suspension in Agitated Vessels

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Flow patterns in agitated vessels are influenced by geometry, particularly impeller diameter and impeller off-bottom clearance. Large impellers and/or high off-bottom clearances lead to reversed flow in which the flow at the base of the vessel is radially-inward as opposed to radially-outward as expected with axial-flow impellers. Reversed flow is detrimental in solids suspension agitation because inordinately high torque and power are required to achieve suspension. This work experimentally characterizes the effect of flow reversal on solids suspension performance, including guidelines for avoiding flow reversal with straight-blade turbines, pitched-blade turbines, and high-efficiency impellers.

Les profils d'écoulement dans les réservoirs agités sont influencés par la géométrie, en particulier par le diamètre de la turbine et le dégagement par rapport au fond de la cuve. Les turbines de grandes dimensions et ayant un dégagement important induisent un écoulement inverse dans lequel l'écoulement à la base du réservoir est centripète, contrairement à l'écoulement centrifuges rencontrés avec les turbines à écoulement axial. L'écoulement inverse n'est pas souhaitable dans l'agitation de suspensions de solides car il faut un couple et une puissance démesurés pour obtenir la mise en suspension. Ce travail expérimental décrit l'effet de l'inversion d'écoulement sur la performance des suspensions de solides et donne des indications pouv éviter l'inversion d'écoulement avec les turbines à pales droites, les turbines à pales inclinées et les turbines à haute efficacité.

Keywords: agitation, solids suspension, flow patterns.

It has become apparent that flow patterns in agitated vessels are not invariant; rather, they are time-dependent and are influenced by Reynolds number (Wang et al., 1995) and geometry. Knowledge of the effect of flow pattern variations can be critical to the success of agitator designs. This paper details the influence of geometric parameters, including impeller type, size, and off-bottom clearance, on flow patterns and agitator performance in turbulent solids suspension applications. These specific solids suspension results indicate the importance of understanding flow pattern effects in this particular application and point to the need to develop a better general understanding of flow pattern effects in agitated systems.

Background

Solids suspension is typically achieved with axial-flow impellers whose discharge flow is directed at the base of the vessel. As the discharge flow impinges on the vessel base, it is redirected in the outward radial direction which leads to suspension of the solid particles at the periphery of the vessel. However, it has been found that if an axial-flow impeller is sufficiently far from the vessel base, its discharge flow will impinge on the vessel wall rather than the base (Jaworski et al., 1991). This leads to two flow loops in the vessel. The primary flow loop heads up the wall, then returns to the impeller at or above the impeller plane. The secondary flow loop is characterized by low-velocity, radially-inward flow at the base of the vessel which returns to the impeller via upflow at the center of the vessel. This flow pattern, which will be referred to as reversed flow, is not well-suited to the suspension of solids because of the high torque and power levels required to achieve acceptable performance. Bakker et al. (1994) have recently demonstrated that computational fluid mixing models do predict flow reversal in agitated vessels.

Figure 1 illustrates the change in flow pattern as impeller off-bottom clearance is increased. These time-averaged turbulent velocity fields were obtained using digital particle image velocimetry (DPIV) (Ward, 1995). The data were taken with a 0.10 m diameter P-4 (pitched-blade) impeller in a 0.29 m (D/T = 0.34) diameter flat-bottomed vessel at off-bottom clearances equal to thirty-three and forty-six percent of the vessel diameter (C/T = 0.33 and 0.46). As shown in Figure 1, at the lower clearance (C/T = 0.33) the typical axial-flow pattern with some upflow directly below the impeller is observed. When the impeller off-bottom clearance is increased (C/T = 0.46), reverse flow occurs and the velocities at the base of the vessel are dramatically reduced (to illustrate the direction of flow, the vector arrowheads are of uniform size in Figure 1, and the length of the vectors reflect the velocity magnitude). It is this reduction in velocity that makes reverse flow undesirable for solids suspension agitation. The flow fields of Figure 1 are slightly asymmetric because the plane of study is displaced approximately 0.01 m from the centerline of the vessel. This is necessary so the agitator shaft will not interfere with the laser light sheet used in the DPIV technique. The details of the DPIV technique will not be discussed here, but are treated in detail by Ward (1995) and Willert and Gharib (1991).

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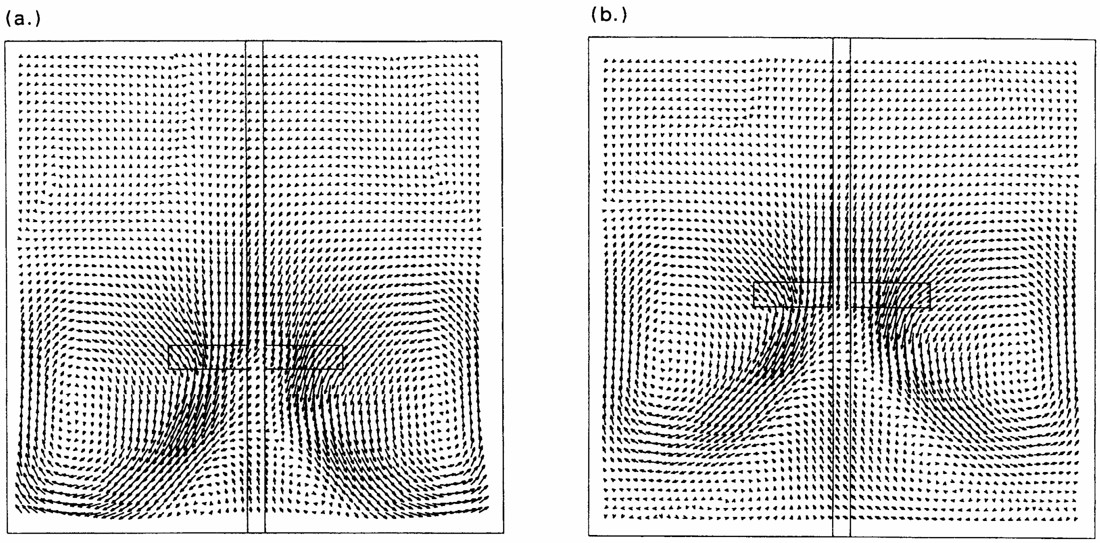

Figure 1 — Flow Patterns of the P-4 Impeller. (a) Axial Flow (D/T = 0.34; C/T = 0.33); (b) Reversed Flow (D/T = 0.34, C/T = 0.46).

The negative impact of this flow pattern transition on the solids suspension performance of axial-flow impellers has been known for a long time. In his pioneering study of solids suspension, Zwietering (1958) noted that this flow pattern transition occurred at an impeller diameter to tank diameter ratio of forty-five percent (D/T = 0.45) for flat-blade propellers. Smaller impellers (D/T < 0.45) provided radially-outward flow on the vessel base and suspended solids at the periphery of the vessel. Larger impellers (D/T > 0.45) led to radially-inward flow and suspension of particles at the center of the vessel. Zwietering did not identify any influence of the impeller off-bottom clearance (C) on this flow pattern transition. Conversely, Gray (1987) observed that this flow pattern transition occurred at impeller off-bottom clearances equal to thirty-five percent of the tank diameter (C/T = 0.35) for pitched-blade turbines operating in flat-bottomed vessels (C/T = 0.37 in dished-bottomed vessels). He found that this transition was independent of the impeller diameter for the range considered (D/T $\leq$ 0.35). Other investigations that have noted the importance of flow pattern on solids suspension performance include those of Nienow and Miles (1978), Conti et al. (1981), and Tiljander and Theliander (1993).

For successful design, it is important to realize that the transition from the anticipated axial-flow pattern to reversed flow with radially-inward flow at the base of the vessel is influenced by both the impeller size (expressed as D/T) and off-bottom clearance (expressed as C/T). Knowledge of this flow transition can be critical as designers are encouraged to reduce solids suspension power requirements through the use of larger impeller diameter to tank diameter ratios (Oldshue, 1969; Obot, 1993; Shaw, 1992). Large diameter impellers are also becoming increasingly necessary to provide the required torque and power to achieve suspension with increased solids loadings (slurries with higher solids content).

As impeller diameter is increased, leading to a corresponding increase in impeller mass, the critical speed of the agitator is decreased. To overcome critical speed limitations, it is often necessary to shorten the shaft which leads to higher impeller off-bottom clearance. As will be shown in this work, the combination of a large diameter impeller and a high off-bottom clearance can lead to poor solids suspension performance and should be avoided in practice.

Experimental apparatus and procedure

A flat-bottomed vessel with a diameter of 0.34 m (13.4 in) was used for all experiments. The vessel was equipped with four vertical baffles of width equal to one-twelfth of the vessel diameter. To prevent stagnant regions the baffles were offset from the vessel base by a distance equal to one-half the baffle width and from the vessel wall by a distance equal to one-sixth of the baffle width. A tall batch was used with a liquid level equal to 1.5 times the tank diameter (Z/T = 1.5) so that the solids suspension performance would not be influenced by air entrainment. Hicks et al. (1993) have demonstrated that liquid level does not affect the just-suspended speed when the solids mass is constant. Further, there were no indications that the tall batch used in these experiments influenced the flow patterns in the vessel, and power numbers measured in the tall batch were essentially identical to those measured with square-batch geometry (Z/T = 1).

The vessel was made of clear acrylic and an angled mirror was used to view the bottom of the vessel. All impeller types were studied at diameters ranging from 0.089 to 0.20 m (3.5 to 8.0 in). This corresponds to impeller diameter to tank diameter ratios of 0.26 $\leq$ D/T $\leq$ 0.60. Power numbers of some impellers (specifically D/T = 0.41) were measured using a calibrated strain gauge reaction torque sensor which yields power numbers with less than five percent error. A hand-held tachometer was used to measure just-suspended speeds and a zero-velocity magnetic pick-up was used to measure impeller speeds during power measurement. Both of the instruments were capable of determining the impeller speed with less than one percent error.

Three impeller types commonly used for solids suspension were investigated (all impellers were supplied by Chemineer, Inc., Dayton, OH). These were Chemineer's high-efficiency HE-3 impeller, a pitched-blade turbine (designated as P-4), and a straight-blade turbine (designated as

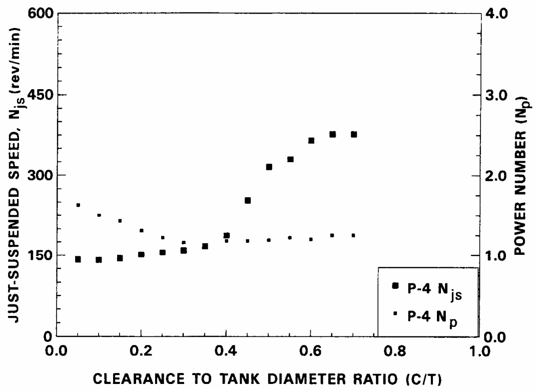

Figure 2 — P-4 Impeller Just-Suspended Speed (N_{js}) and Power Number (N_p) Dependence on Off-Bottom Clearance (D/T = 0.41).

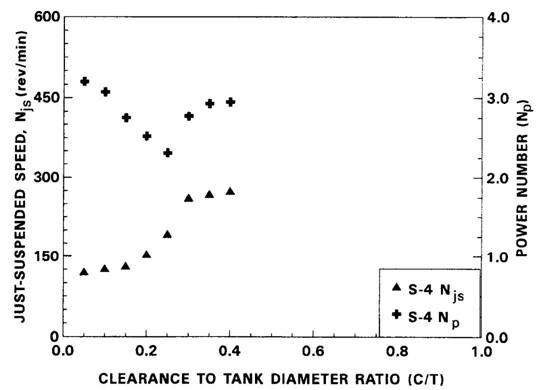

Figure 3 — S-4 Impeller Just-Suspended Speed (N_{js}) and Power Number (N_p) Dependence on Off-Bottom Clearance (D/T = 0.41).

S-4). The HE-3 was of standard construction. The P-4 was a four-bladed turbine with blade angles of forty-five degrees and a blade width to impeller diameter ratio of W/D = 0.20. The S-4 was a four-bladed, straight-blade turbine (corresponding to blade angles of ninety degrees) with blade widths equal to one-sixth of the impeller diameter (W/D = 0.167). Although the S-4 is not as commonly used for solids suspension as the HE-3 and P-4, it is often used as a tickler impeller. In these instances a small S-4 is placed below a larger, primary solids suspension impeller. The purpose of the S-4 is to ensure solids suspension whenever the liquid level is below the primary solids suspension impeller.

A number of solids were considered; however, the results did not vary substantially with the type of solid, so only data taken with one representative material will be presented. This solid was 3000-μm acrylic beads with a density of 1180 kg/m^3 and a measured settling velocity of 0.077 m/s in water (the liquid medium used for the study). The particles were very uniform in size, and their shape was cylindrical with an oval cross section. Also, the solid loading, studied up to twenty mass percent, did not affect the results. The data presented here was all taken with a slurry that was five percent solids by mass. The lowest Archimedes number ($d_p^3 g(\rho_s-\rho_l)/\rho_l \nu^2$) that was considered was 250. According to the studies of Molerus and Latzel (1987a,b), these are coarse-grained particles for which bulk flow is critical for suspension. The applicability of the present results to fine particles (Archimedes number less than about forty) which are suspended by boundary layer flow at the vessel base is uncertain. Therefore, this study does not address the industrially important subject of powder suspension.

For all impeller types and sizes, the just-suspended speed was determined by visual inspection at off-bottom clearances corresponding to five, ten, fifteen, etc. percent of the vessel diameter (C/T = 0.05, 0.10, 0.15, ...). The off-bottom clearance was increased until reverse flow was observed. This would be apparent by the tendency for solids to pile at the center of the vessel and the dramatic increase in just-suspended speed. Zwietering's (1958) two-second just-suspended speed criterion was used, and a repeatability of three percent was achieved.

Results and discussion

Figure 2 illustrates the influence of off-bottom clearance on the just-suspended speed of a P-4 impeller with an impeller diameter to tank diameter ratio of D/T = 0.41. At low clearances (C/T < 0.40), the just-suspended speed increases slowly as the off-bottom clearance is increased. At these clearances, the flow at the base of the vessel is radially-outward and the solids are suspended at the periphery of the vessel. At a clearance of C/T = 0.40, the flow pattern shows indications of changing as the solids are suspended at both the periphery and center of the vessel. As the clearance is increased to forty-five percent of the vessel diameter or greater (C/T ≥ 0.45), reversed flow occurs which is accompanied by a dramatic increase in the just-suspended speed.

Figure 3 presents just-suspended speed data for the S-4 impeller. The flow pattern transitions for the S-4 are essentially the same as those of the P-4 with radially-outward flow at low clearances (C/T ≤ 0.15), a transitional flow at an intermediate clearance (C/T = 0.20), and reversed flow at high clearances (C/T ≥ 0.25).

The behavior of the HE-3 impeller is depicted in Figure 4. In this instance, because of the highly axial discharge flow of the HE-3 impeller, complete flow reversal does not occur until the off-bottom clearance is ninety-five percent of the vessel diameter (C/T = 0.95). However, for clearances greater than seventy percent of the vessel diameter (C/T > 0.70), the just-suspended speed increases at a greater rate because much of the energy of the impeller discharge stream is dissipated before the flow reaches the base of the vessel. The impeller still suspends the solids reasonably well, but requires higher torque and power levels. Therefore, the maximum recommended off-bottom clearance is taken as seventy percent of the vessel diameter. At larger impeller diameter to tank diameter ratios (D/T > 0.50), the HE-3 impeller does experience flow reversal at lower off-bottom clearances.

Figures 2-4 also demonstrate the influence of off-bottom clearance on power number, as well as just-suspended speed. Conti et al. (1981) found that the power number and just-suspended speed of an eight-bladed disc impeller increased simultaneously as the impeller off-bottom clearance was increased and flow reversal occurred. This exact type of behavior was not observed for any of the impellers studied here. The power number of the P-4 impeller decreases with increasing off-bottom clearance until it reaches an asymptotic value for clearances which lead to flow reversal (refer to Figure 2). Similarly, the power number of the S-4

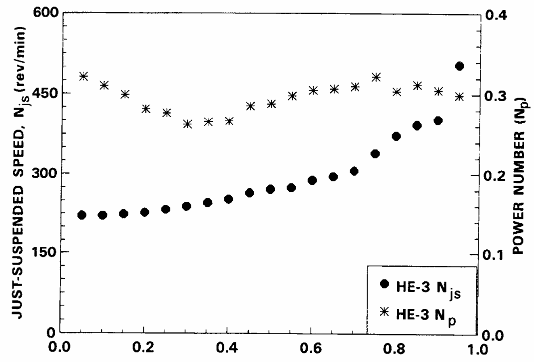

Figure 4 — HE-3 Impeller Just-Suspended Speed (N_{js}) and Power Number (N_p) Dependence on Off-Bottom Clearance (D/T = 0.41).

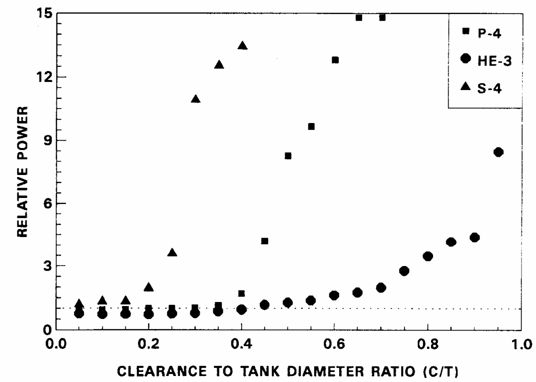

Figure 6 — P-4, HE-3, and S-4 Just-Suspended Power Requirements Dependence on Off-Bottom Clearance (D/T = 0.41; all power requirements are normalized with respect to those of the P-4 impeller at C/T = 0.25).

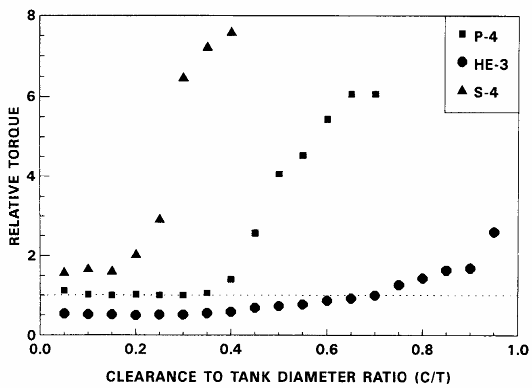

Figure 5 — P-4, HE-3, and S-4 Just-Suspended Torque Requirements Dependence on Off-Bottom Clearance (D/T = 0.41; torque requirements are normalized with respect to those of the P-4 impeller at C/T = 0.25).

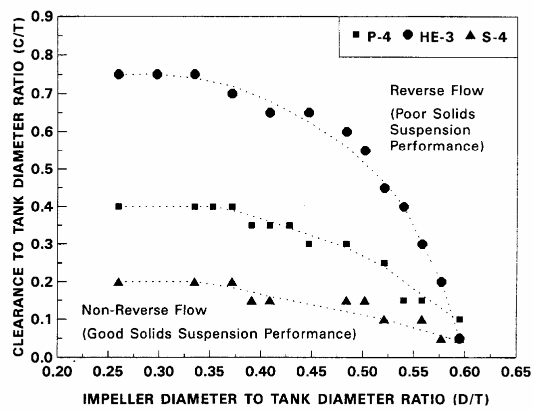

Figure 7 — Map Illustrating the Highest Off-Bottom Clearance for Acceptable Solids Suspension Performance with the P-4, HE-3, and S-4 Impellers.

decreases with increasing off-bottom clearance (refer to Figure 3), increasing again at higher off-bottom clearances (C/T ≥ 0.30) similar to the behavior observed by Conti et al. (1981). However, the lowest clearance at which flow reversal occurs (C/T = 0.25) actually corresponds to the lowest power number (i.e., the increase in power number occurs at a higher clearance than flow reversal). The power number of the HE-3 impeller is also influenced by off-bottom clearance, but there is no clear relation between power number, just-suspended speed, and flow pattern (refer to Figure 4).

The just-suspended speed and power number information of Figures 2-4 (with D/T = 0.41) can be combined to determine just-suspended torque and power requirements which determine capital and operating expenses, respectively. The dependence of the just-suspended torque on impeller off-bottom clearance is presented in Figure 5 (the power requirements of Figure 6 show similar trends, but are more pronounced since torque is proportional to impeller speed squared and power is proportional to impeller speed cubed). All torque and power requirements have been normalized with respect to those of the P-4 impeller at a clearance of one-fourth of the vessel diameter (C/T = 0.25). Figures 5 and 6 clearly illustrate that the HE-3 impeller is most efficient at solids suspension, while the S-4 impeller is the least efficient.

Figures 5 and 6 also illustrate the upper limits of off-bottom clearance for solids suspension before flow reversal causes the torque and power requirements to increase dramatically. At this impeller diameter to tank diameter ratio (D/T = 0.41), the S-4 impeller should only be used for clearances less than or equal to twenty percent of the vessel diameter (C/T ≤ 0.20); the P-4 should only be used for clearances less than forty percent of the vessel diameter (C/T ≤ 0.40); and the HE-3 should only be used for clearances less than or equal to seventy percent of the vessel diameter (C/T ≤ 0.70), although this point is more difficult to choose since complete flow reversal does not actually occur until higher clearances (C/T ≥ 0.95).

The point of flow reversal for other impeller diameter to tank diameter ratios can be determined in a similar manner. This leads to the map of Figure 7 which indicates the highest recommended clearance (expressed as C/T) for a given impeller diameter (expressed as D/T). This figure clearly illustrates that larger impellers must be located closer to the vessel base to achieve acceptable solids suspension performance. Also, the HE-3, which has a highly-axial discharge flow, provides the greatest geometric flexibility. The P-4, whose discharge flow is mixed (with substantial axial and radial components), provides intermediate flexibility. And the S-4, primarily a radial-flow impeller, must be placed very near the vessel base. However, this will typically be the case when this impeller is used as a tickler below the primary solids suspension impeller. Recall that the results of Figure 7 are limited to coarse-grained particles according to the work of Molerus and Latzel (1987a,b).

The data presented in Figure 7 agree reasonably well with previous studies. Gray (1987) reported that a flow pattern transition occurred at impeller off-bottom clearances equal to thirty-five percent of the tank diameter (C/T = 0.35) for pitched-blade turbines operating in flat-bottomed vessels. For the range of impeller diameter to tank diameter ratios studied (D/T $\leq$ 0.35), this point of transition was found to be independent of the impeller diameter. This current study found the flow pattern transition to occur at a slightly higher off-bottom clearance (C/T = 0.40) and also to be independent of impeller diameter at smaller impeller diameter to tank diameter ratios.

Kresta and Wood (1993) observed a flow pattern transition at an off-bottom clearance equal to sixty percent of the impeller diameter (C/D = 0.60) with a pitched-blade turbine in a flat-bottomed vessel. This flow pattern transition only occurred for the larger impeller studied (D/T = 0.50), not for the smaller impeller (D/T = 0.25). The given impeller off-bottom clearance (C/D = 0.60) corresponds to thirty-percent of the vessel diameter (C/T = 0.30) which agrees with the data presented in Figure 7 at an impeller diameter to tank diameter ratio of fifty percent.

Conti et al. (1981) found that flow reversal occurs at an off-bottom clearance of twenty-two percent of the vessel diameter (C/T = 0.22) for an eight-bladed disc turbine (0.22 $\leq$ D/T $\leq$ 0.37). The results obtained in this study with the S-4 impeller are very similar, with flow reversal being observed for impeller off-bottom clearances greater than twenty percent of the vessel diameter (C/T > 0.20) for small impellers (D/T < 0.35). Since both S-4 and disc impellers are primarily radial-flow devices, it is expected that they would exhibit similar behavior with respect to flow pattern transitions.

Concluding remarks

The fact that flow patterns in agitated vessels are not invariant is now understood. However, little previous work has been done to characterize the effects of flow pattern changes on agitator performance. The work presented here illustrates the importance of geometric design parameters (C/T - D/T combinations) on just-suspended speed requirements (and the associated torque and power requirements). In particular, geometries that lead to reversed flow, undesirable for solids suspension, have been identified for three impellers commonly used in solids suspension applications. Since the results presented here were obtained with coarse-grained particles (Archimedes numbers greater than 250), the question remains whether flow reversal occurs and is important in the suspension of fine particles (Archimedes numbers less than about forty). Given the demonstrated importance of flow pattern on solids suspension performance, the influence of flow pattern changes, whether caused by Reynolds number, geometry, or time dependence, should be given greater consideration in other agitator applications.

Nomenclature

C = impeller off-bottom clearance (measured from the lowest point on the impeller), m
d_p = particle diameter, m
D = impeller diameter, m
g = acceleration of gravity, m/s^2
N = impeller speed, rev/min
N_{js} = just-suspended speed, rev/min
N_p = power number, $N_p = P/\rho N^3 D^5$, dimensionless
P = impeller power draw, W
T = vessel diameter, m
W = impeller blade width, m
Z = liquid level, m

Greek letters

ν = kinematic viscosity, m^2/s
ρ = density, kg/m^3

Subscripts

l = refers to liquid
s = refers to solid

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