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Solids Suspension with Up-Pumping Pitched-Blade and High-Efficiency Impellers

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The use of axial-flow impellers in the up-pumping mode has been increasing, but little performance and design information is available. Up-pumping pitched-blade and high-efficiency impellers have been studied in solids suspension applications, and their performance has been compared to and contrasted with that of the more conventional down-pumping mode. Just-suspended speed data has been interpreted in terms of two literature correlations that can be used for design purposes. Just-suspended torque and power requirements are presented, as well as turbulent power number and flow pattern data. In general, the just-suspended torque and power requirements of up-pumping pitched-blade and high-efficiency impellers are substantially higher than those of the down-pumping mode. However, if a large impeller diameter is required to avoid critical speed limitations or to achieve sufficient power inputs at high solids loadings, then up-pumping impellers may be a viable option.

L'utilisation de turbines à écoulement axial en pompage ascendant s'est accrue, mais il existe peu d'informations sur leurs performances et leurs conceptions. Des turbines à pales inclinées et des turbines à grand rendement en pompage ascendant ont été étudiés dans des applications de suspensions de solides et leur performance a été comparée et mise en perspective par rapport au mode de pompage descendant plus conventionnel. Des données de vitesse de mise en suspension critique ont été interprétées relativement à deux corrélations de la littérature scientifique, qui peuvent servir à des fins de conception. Le couple de mise en suspension critique et la consommation de puissance sont présentés, ainsi que le nombre de puissance turbulent et les données de profils d'écoulement. En général, le couple de mise en suspension critique et la consommation de puissance des turbines à pales inclinées et des turbines à grand rendement en pompage ascendant sont substantiellement plus élevés que dans le cas du mode descendant. Cependant, si un gros diamètre de turbine est nécessaire pour éviter les limitations de vitesse critique ou pour obtenir des consommations de puissance suffisantes à des taux de solides élevés, alors les turbines en pompage ascendant peuvent être une option viable.

Keywords: solids suspension, up-pumping impellers, pitched-blade impellers, high-efficiency impellers.

The up-pumping mode of agitation has been growing in popularity, particularly in gas dispersion operations (Nienow et al., 1997; Post, 1997). However, much of the evidence of up-pumping performance characteristics is anecdotal, and little design information is available in the literature. Recently, Ibrahim and Nienow have reported the power draw characteristics (1995) and solids suspension performance (1996) of an up-pumping 6-blade 45° pitched-blade turbine. They reported that the just-suspended power requirements of the up-pumping pitched-blade turbine were lower than those of radial-flow turbines and large-diameter down-pumping pitched-blade turbines (D/T = 0.52), but higher than those of small-diameter down-pumping pitched-blade turbines (D/T = 0.38) and the Lightnin A310 and Chemineer HE-3 high-efficiency impellers. In three-phase (gas–liquid–solid) operation, up-pumping impellers have been found to provide very stable operation, unlike the down-pumping mode which is subject to substantial torque and power fluctuations at all but the lowest gas flow rates. However, at these low gas flow rates the power requirements in the down-pumping mode are lower than in the up-pumping mode (Frijlink et al., 1990; Chapman et al., 1983).

This work focuses on the effect of system geometry (D/T and C/T) on the solids suspension performance of up-pumping pitched-blade and high-efficiency impellers in both flat and dish-bottom vessels. Data presented includes flow patterns, turbulent power numbers, and just-suspended speed, torque, and power requirements. The just-suspended speed data is interpreted in terms of the design correlations of Zwietering (1958) and Corpstein et al. (1994). Also, the up-pumping solids suspension performance is compared to and contrasted with that of the down-pumping mode.

Experimental apparatus and procedures

Experiments were performed in cylindrical flat and dish-bottom vessels with inner diameters of 0.442 m. Both vessels were equipped with four baffles placed at 90° around the vessel periphery. The baffle widths were equal to one-twelfth of the vessel diameter ($T/12$), and they were offset from the vessel wall by a distance equal to one-seventy second of the vessel diameter ($T/72$). The baffles ran the entire length of the vessel straight side in the dish-bottom vessel, and were placed at a clearance of one-half the baffle width from the base of the flat-bottom vessel (Myers and Fasano, 1992).

Two common solids suspension impeller types were studied. The P-4 impeller is a 4-blade, 45° pitched-blade turbine with blade widths equal to one-fifth of the impeller diameter (W/D = 0.2; this refers to the actual, not projected, blade width). The HE-3 impeller is a narrow-blade, 3-blade high-efficiency impeller of standard construction. All impellers were supplied by Chemineer, Inc. (Dayton, OH). Impellers with diameters of 0.108, 0.152, 0.197, and 0.241 m were used, corresponding to impeller diameter to tank diameter ratios (D/T) of 0.24, 0.34, 0.45, and 0.55. Square-batch geometry (Z/T = 1) was used in all instances. Impeller off-bottom clearance to tank diameter ratios (C/T) of 0.05, 0.15, 0.25, 0.35, and 0.45 were studied, with the off-bottom clearances

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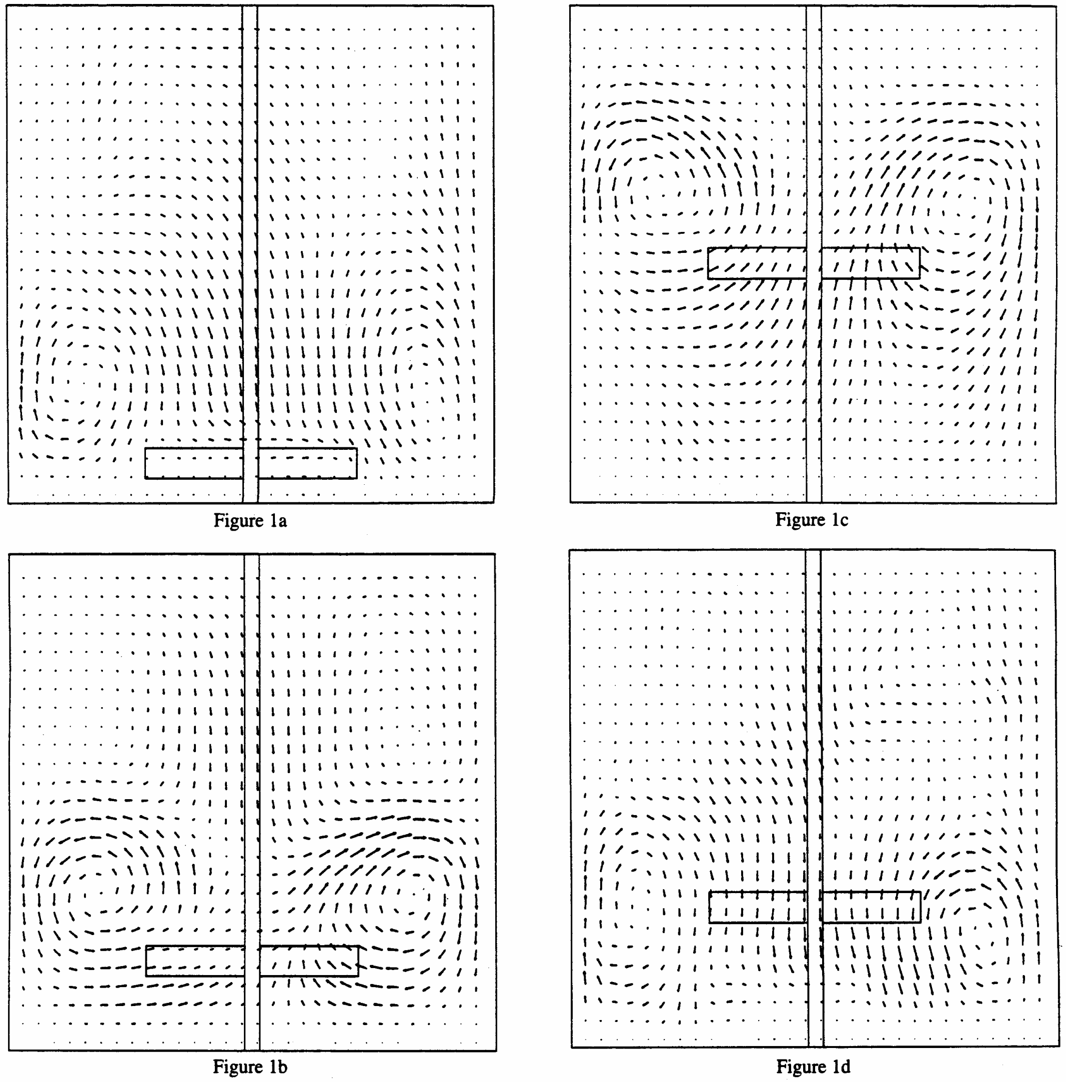

Figure 1 — Flow patterns of the P-4 impeller in a flat-bottom vessel (D/T = 0.43). (a) Up- pumping at C/T = 0.05; (b) Up-pumping at C/T = 0.15; (c) Up-pumping at C/T = 0.45; (d) Down-pumping at C/T = 0.25.

being measured from the lowest point on the impeller to the lowest point on the vessel base. It was not always possible to determine the just-suspended speed at the highest off-bottom clearances with the up-pumping impellers because of the excessively high speeds required to achieve suspension.

The effect of liquid coverage over the impeller was not studied except implicitly through the study of impeller off-bottom clearance. Liquid coverage may be an important parameter in determining power draw and flow pattern for up-pumping impellers, particularly when they are placed high in the liquid to generate surface motion.

The solid particles used in this work were acrylic with a characteristic length dimension of 2950 microns, a roughly cubic shape, a density of 1180 kg/m^3, and a settling velocity of 0.077 m/s in water, the only liquid used (this is the settling velocity of a single particle in quiescent liquid). A solids loading (solids mass/slurry mass) of 10% was used in the flat-bottom vessel, and the same solids mass was used in the dish-bottom vessel (corresponding to a solids loading of 10.8 percent).

Power number data was taken in water using a calibrated reaction torque cell and a zero velocity magnetic pickup for speed measurement. The vessels were constructed of clear acrylic, and angled mirrors were used to view the bottom of the vessel. Just-suspended speeds were determined visually using Zwietering's (1958) 2 s criterion. Eliminating bias from visual interpretation of solids suspension experiments is difficult. To maintain the highest possible degree of consistency, experiments were performed using twin side-by-side vessels (Corpstein and Dickey, 1983). One vessel contained

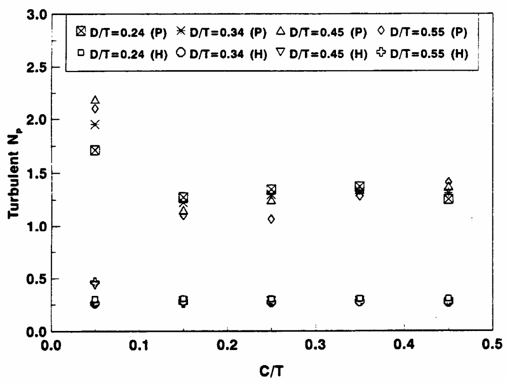

Figure 2 — Turbulent power numbers of up-pumping P-4 (P) and HE-3 (H) impellers in the dish-bottom vessel.

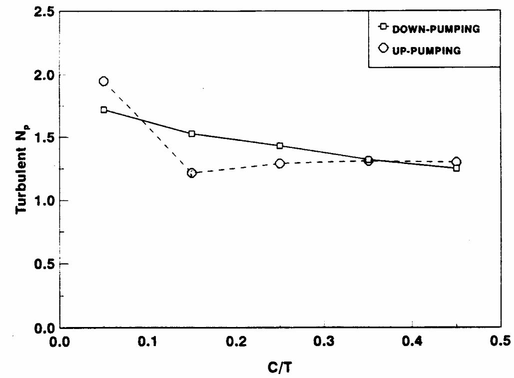

Figure 3 — Comparison of the up-pumping and down-pumping turbulent power numbers of the P-4 impeller in the dish-bottom vessel ($D/T = 0.34$).

the impeller system to be studied, while the other vessel was used as a reference impeller system operating at just-suspended conditions. The reference system was a down-pumping P-4 impeller in a flat-bottom vessel with an impeller diameter to tank diameter ratio of 34% and an off-bottom clearance equal to 25% of the vessel diameter ($D/T = 0.34$ and $C/T = 0.25$). Although this study focused on the up-pumping mode of operation, power number and just-suspended speed data was also taken in the down-pumping mode for comparison. All data was taken in the turbulent regime, with impeller Reynolds numbers exceeding 10 000.

Time-averaged liquid-only velocity fields were obtained using digital particle image velocimetry (DPIV; Myers et al., 1997). A 0.127-m diameter P-4 impeller was studied in a 0.292-m diameter flat-bottom vessel ($D/T = 0.43$) at various off-bottom clearances ($C/T = 0.05$, 0.15, and 0.45). The liquid phase was water, and the speed was 1 s^{-1} (60 rpm), corresponding to an impeller Reynolds number of 16 100. The plane of study was located 0.01 m from the centerline of the vessel, just in front of the plane defined by the shaft and two baffles. This caused some asymmetry in the flow fields. In the up-pumping mode, the left-hand side of the flow field is behind a baffle and the right-hand side of the flow field is in front of a baffle (with in front and behind being determined relative to the direction of rotation of the impeller). Conversely, in the down-pumping mode, the left-hand side of the flow field is in front of a baffle and the right-hand side of the flow field is behind a baffle.

Flow pattern results

Figures 1a through 1c illustrate the flow patterns produced by an up-pumping P-4 impeller in a flat-bottom vessel, while Figure 1d presents the down-pumping flow pattern (at $C/T = 0.25$) for comparison. Note that the vector lengths are proportional to the liquid velocity. At the lowest impeller off-bottom clearance ($C/T = 0.05$ in Figure 1a), the flow pattern is not up-pumping. In fact, the flow pattern is opposite of what is expected, with the inlet flow to the impeller being from above and the discharge flow being radial. This radial flow pattern was always observed for the P-4 impeller at the lowest impeller off-bottom clearance ($C/T = 0.05$) except for the smallest impeller ($D/T = 0.24$) in the flat-bottom vessel. This radial flow pattern was observed with the HE-3 impeller only in a few instances ($D/T = 0.45$ and 0.55 at $C/T = 0.05$ in the dish-bottom vessel).

At an intermediate impeller off-bottom clearance ($C/T = 0.15$ in Figure 1b), the P-4 flow pattern is up-pumping, with the impeller discharge flow flaring out towards the vessel wall. This leads to a secondary flow loop in the upper half of the vessel. This flow pattern agrees with that recently reported by Birch and Ahmed (1997) for an up-pumping 6-blade pitched-blade disc turbine. At the highest impeller off-bottom clearance ($C/T = 0.45$ in Figure 1c), the flow pattern is very similar to that at the intermediate impeller off-bottom clearance ($C/T = 0.15$), except that due to the high impeller placement, the upper flow loop is very small as the discharge flow almost reaches the liquid surface. Also, since the impeller is far from the vessel base, the fluid velocity is very low in this region.

Power number results

The turbulent power numbers of up-pumping P-4 and HE-3 impellers in the dish-bottom vessel are presented in Figure 2. In general, these turbulent power numbers are not strongly influenced by system geometry (C/T and D/T). However, if radial flow occurs at the lowest impeller off-bottom clearance ($C/T = 0.05$; refer to the flow pattern of Figure 1a), the turbulent power numbers of both impellers increase dramatically, by as much as 50% in some instances. Ibrahim and Nienow (1995) found similar, limited geometric influences for an up-pumping 6-blade, pitched-blade impeller in a flat-bottom vessel. For an intermediate impeller diameter ($D/T = 0.38$), they reported that the turbulent power number was independent of off- bottom clearance, while for a large impeller diameter ($D/T = 0.52$), the power number decreased slightly with decreasing off-bottom clearance. These workers did not consider the very low impeller off-bottom clearances that lead to radial flow behavior and high power numbers.

The turbulent power numbers of the up-pumping impellers are essentially unaffected by vessel base shape except at the lowest impeller off-bottom clearance (when radial flow may occur in the dish-bottom vessel but not in the flat-bottom vessel). Excluding these conditions, the average absolute difference between the turbulent power numbers in flat and dish-bottom vessels was found to be 5% for the P-4 and 2% for the HE-3. Similarly, the down-pumping turbulent power number of the HE-3 impeller was found to be independent of vessel base shape. In contrast, the down-pumping turbulent power number of the P-4 impeller averaged 12% higher in the dish-bottom vessel than in the flat-bottom vessel.

The turbulent power numbers in the up-pumping mode were found to be similar to, but not the same as, those in the down-pumping mode. The average absolute difference was 11% for the P-4 impeller and 6% for the HE-3, with the largest differences occurring at low impeller off-bottom clearances ($C/T < 0.25$). These differences are illustrated for the P-4 impeller in the dish-bottom vessel (at $D/T = 0.34$) in Figure 3. Note that the lines in this figure are not data correlations; rather, they are only intended to indicate data trends. Although the up and down-pumping power numbers are similar, the trends with respect to impeller off-bottom clearance are different. While the power number in the down-pumping mode continually decreases with increasing off-bottom clearance, the power number in the up-pumping mode is practically independent of off-bottom clearance except for the very high power number associated with the radial flow pattern at the lowest off-bottom clearance.

Solids suspension results

The influence of geometry on the measured just-suspended speeds of the up-pumping P-4 impeller can be described within the studied range with reasonable accuracy by the following simple power-law relations.

$$N_{js}(P-4, \textit{flat bottom}) \propto \left(\frac{C}{T}\right)^{0.308}\left(\frac{D}{T}\right)^{-2.51} \quad \ldots\ldots \text{(1a)}$$

$$N_{js}(P-4, \textit{dish bottom}) \propto \left(\frac{C}{T}\right)^{0.357}\left(\frac{D}{T}\right)^{-2.48} \quad \ldots\ldots \text{(1b)}$$

These strong dependencies of the just-suspended speed on impeller off-bottom clearance may appear to conflict with Ibrahim and Nienow's (1996) finding that the just-suspended speed of an up-pumping 6-blade pitched-blade turbine is practically independent of off-bottom clearance in a flat-bottom vessel ($N_{js} \propto (C/T)^{0.05}$ for $D/T = 0.52$ and $0.17 \leq C/T \leq 0.33$). However, if the data from the present study is limited to conditions similar to those of Ibrahim and Nienow ($D/T = 0.55$ and $0.15 \leq C/T \leq 0.35$), then a reduced dependence on impeller off-bottom clearance is found ($N_{js} \propto (C/T)^{0.13}$ in the flat-bottom vessel and $N_{js} \propto (C/T)^{0.15}$ in the dish-bottom vessel).

As noted by Ibrahim and Nienow (1996), generalization of just-suspended speed data in terms of a design correlation increases the utility of the data. The just-suspended speed data of this work has been interpreted in terms of two common design correlations. The first is the classic just-suspended speed correlation of Zwietering (1958) which describes impeller type and system geometry effects in terms of an S factor that is believed to be independent of solid and liquid properties, solids loading, and scale. Rearrangement of Zwietering's just-suspended speed correlation allows the S factor to be calculated from just-suspended speed data.

$$S = \frac{N_{js}D^{0.85}}{\nu^{0.1}d_p^{0.2}\left(\frac{g(\rho_s-\rho_l)}{\rho_l}\right)^{0.45}B^{0.13}} \quad \ldots\ldots\ldots\ldots\ldots \text{(2)}$$

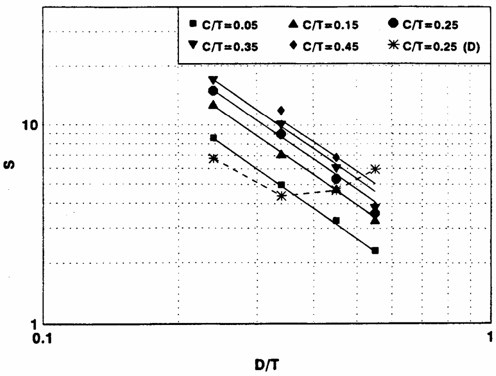

Figure 4 — Zwietering S factor for the up-pumping P-4 impeller in the dish-bottom vessel; solid lines represent the correlation of Equation (3b); D refers to data taken in the down-pumping mode (this data is connected by a dashed line for clarity, not to represent a correlation).

The up-pumping P-4 just-suspended speed relations of Equation (1) can be expressed in terms of S factors as follows.

$$S(P-4, \textit{flat bottom}) = 2.55\left(\frac{C}{T}\right)^{0.308}\left(\frac{D}{T}\right)^{-1.66} \quad \ldots\ldots \text{(3a)}$$

$$S(P-4, \textit{dish bottom}) = 2.47\left(\frac{C}{T}\right)^{0.357}\left(\frac{D}{T}\right)^{-1.63} \quad \ldots \text{(3b)}$$

These expressions are accurate, with average absolute errors of 4.5% (flat-bottom vessel) and 5.4% (dish-bottom vessel). The dish-bottom vessel correlation is compared to the experimental S values in Figure 4, and the agreement can be seen to be very good except for the largest impeller ($D/T = 0.55$) at high off-bottom clearances ($C/T \geq 0.25$), where the correlation overpredicts the experimental S values. The solid lines in Figure 4 represent the correlation of Equation (3b). In all other figures, lines connecting data points are only intended to clarify data trends, not to represent a correlating equation.

The experimental S values determined for a down-pumping P-4 impeller (at $C/T = 0.25$) are also shown in Figure 4 (these data points are connected by a dashed line for clarity, not to represent a correlation of the data). In the down-pumping mode, the S values increase at large impeller diameter to tank diameter ratios because of flow reversal (Myers et al., 1996). Under these conditions the discharge flow from a down-pumping impeller impinges on the vessel wall rather than the base, leading to low-velocity, radially-inward flow on the vessel base. Because of the low velocities near the vessel base, down-pumping solids suspension with the reversed flow pattern requires increased speeds.

Because of the more complex interaction between impeller diameter to tank diameter ratio and impeller off-bottom clearance (D/T and C/T), the just-suspended speed data of the up-pumping HE-3 impeller cannot be correlated as simply or accurately as that of the up-pumping P-4 impeller with power-law relations; however, the following correlations were developed for the Zwietering S factor.

$$S(HE-3, \textit{flat bottom}) = 2.05\left(\frac{D}{T}\right)^{-2.82}\left(\frac{C}{T}\right)^{\left[0.106\left(\frac{D}{T}\right)^{-1.25}\right]} \quad \ldots\ldots\ldots\ldots \text{(4a)}$$

$$S(HE-3, dish\,bottom)$$

$$= 2.21\left(\frac{D}{T}\right)^{-1.32} \exp\left[\left(4.47 - 5.71\left(\frac{D}{T}\right)\right)\left(\frac{C}{T}\right)\right] \quad \ldots \text{(4b)}$$

The average absolute errors of these correlations are 6.3% (flat-bottom vessel) and 8.2% (dish-bottom vessel).

A second design correlation, proposed by Corpstein et al. (1994), correlates the just-suspended speed in terms of the terminal particle settling velocity in a quiescent fluid.

$$N_{js} = k\left[\left(\frac{\rho_s - \rho_l}{\rho_l}\right)u_t\right]^{0.28} f(X) f\left(\frac{D}{T}, \frac{C}{T}\right)\left(\frac{T}{T_o}\right)^{-n} \quad \ldots \text{(5)}$$

k is an impeller constant, and $f(X)$ and $f(D/T, C/T)$ describe the effects of solids loading and geometry, respectively (provided graphically in Figures 1 and 2 of their paper). Note that Zwietering's (1958) just-suspended correlation of Equation (2) can be applied with any consistent set of units, while the correlation of Equation (5) requires use of the SI units specified in the nomenclature. In contrast to Zwietering's correlation that uses a constant scaleup exponent of 0.85, the correlation of Corpstein et al. incorporates a scaleup exponent that varies with particle settling velocity (presented as a graphical correlation in Figure 4 of their paper). Suspension of very slowly settling particles scales up with an exponent near unity, much like scaleup of liquid motion agitation (Fasano et al., 1994). As the particle settling velocity increases, the solids suspension scaleup exponent decreases, reaching a lower asymptotic value of 0.5 for rapidly settling particles.

In the down-pumping mode, Corpstein et al. (1994) reported the following impeller constants

k(P-4,down-pumping) = 15.0
k(HE-3,down-pumping) = 23.0

independent of the vessel base shape. The geometric parameter $f(D/T, C/T)$ was presented graphically (refer to Figure 2 of their paper; actually, $f(D/T)$ was presented, with off-bottom clearance effects being minimal in down-pumping solids suspension with the P-4 and HE-3 impellers). The up-pumping data of this work leads to the following impeller constants

k(P-4,up-pumping,flat bottom) = 28.6
k(HE-3,up-pumping,flat bottom) = 69.9
k(P-4,up-pumping,dish bottom) = 27.4
k(HE-3,up-pumping,dish bottom) = 58.1

and the following geometric parameters.

$$P-4(up, flat\,bottom): f\left(\frac{D}{T}, \frac{C}{T}\right)$$

$$= 0.110\left(\frac{D}{T}\right)^{-2.51}\left(\frac{C}{T}\right)^{0.308} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(6a)}$$

$$P-4(up, dish\,bottom): f\left(\frac{D}{T}, \frac{C}{T}\right)$$

$$= 0.121\left(\frac{D}{T}\right)^{-2.48}\left(\frac{C}{T}\right)^{0.357} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(6b)}$$

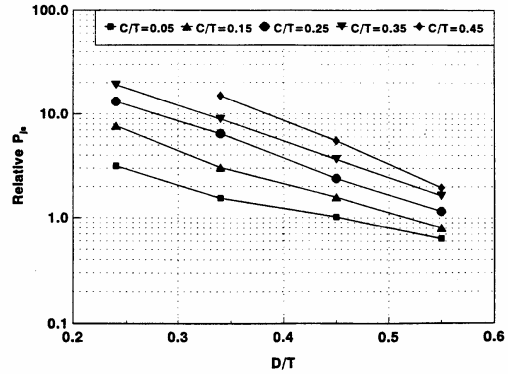

Figure 5 — Relative just-suspended power requirements of the up-pumping P-4 impeller in the dish-bottom vessel.

$$HE-3(up, flat\,bottom): f\left(\frac{D}{T}, \frac{C}{T}\right)$$

$$= 0.0366\left(\frac{C}{T}\right)^{\left[0.106\left(\frac{D}{T}\right)^{-1.25}\right]}\left(\frac{D}{T}\right)^{-3.67} \quad \ldots\ldots\ldots\ldots \text{(6c)}$$

$$HE-3(up, dish\,bottom): f\left(\frac{D}{T}, \frac{C}{T}\right)$$

$$= 0.0552\left(\frac{D}{T}\right)^{-2.17} \exp\left[\left(4.47 - 5.71\left(\frac{D}{T}\right)\right)\left(\frac{C}{T}\right)\right] \quad \ldots \text{(6d)}$$

The experimental power numbers and just-suspended speeds can be combined to determine the just-suspended torque and power requirements for up-pumping impellers. Torque is an important parameter because it is the primary factor in determining the size of the gear drive, and therefore the capital cost, of an agitator. Power, on the other hand, determines the operating cost. Figure 5 presents the just-suspended power requirements for up-pumping P-4 impellers in the dish-bottom vessel which are expressed relative to those of the reference system (a down-pumping P-4 impeller in a flat-bottom vessel with D/T = 0.34 and C/T = 0.25). The just-suspended power requirements increase with increasing impeller off-bottom clearance and decrease with increasing impeller diameter to tank diameter ratio. Just-suspended torque also increases with increasing impeller off-bottom clearance and is relatively independent of impeller diameter to tank diameter ratio, decreasing somewhat for the larger impellers (D/T = 0.45 and 0.55; the just-suspended torque requirements are not shown in a figure). Although the data of Figure 5 is for the P-4 impeller in the dish-bottom vessel, similar trends were observed for the HE-3 impeller in the dish-bottom vessel and for both impellers in the flat-bottom vessel.

Figure 6 compares the impact of impeller off-bottom clearance on the just-suspended torque requirements of up and down-pumping P-4 impellers in the flat-bottom vessel (at D/T = 0.34; comparison of the just-suspended powers would be similar). For the lower off-bottom clearances (0.05 ≤ C/T ≤ 0.35), the relative just-suspended torque in the down-pumping mode varies by only about 20%, ranging from 0.92 to 1.1. Even at the highest off-bottom clearance

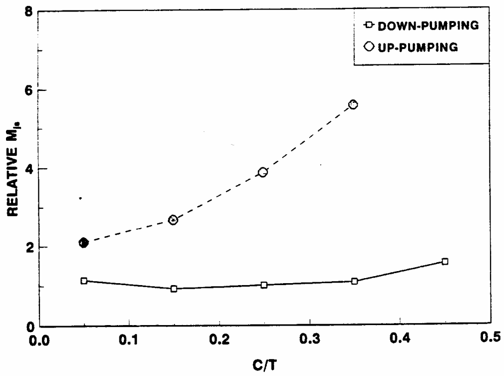

Figure 6 — Comparison of the influence of impeller off-bottom clearance on the relative just- suspended torque requirements of up-pumping and down-pumping P-4 impellers in the flat-bottom vessel ($D/T = 0.34$).

($C/T = 0.55$), the relative just-suspended torque in the down-pumping mode only increases to 1.5 as the point of flow reversal is approached. Conversely, in the up-pumping mode, the relative just-suspended torque increases rapidly as the impeller off-bottom clearance increases (varying from 2.1 at $C/T = 0.05$ to 5.6 at $C/T = 0.35$). The just-suspended torque for up-pumping impellers is less sensitive to impeller off-bottom clearance for the largest impeller diameter to tank diameter ratio studied ($D/T = 0.55$; this can be inferred from the just-suspended speed data of Figure 4).

Figure 7 compares the just-suspended power requirements, in both the flat and dish-bottom vessels, of up-pumping and down-pumping HE-3 and P-4 impellers. Again, these power requirements have been normalized with respect to those of the reference system (a down-pumping P-4 impeller in a flat-bottom vessel with D/T = 0.34 and C/T = 0.25). All of the data of Figure 7 was obtained at an impeller off-bottom clearance equal to 25% of the vessel diameter ($C/T = 0.25$), a typical configuration for solids suspension. The just-suspended power of the down-pumping HE-3 is 20 to 75% lower than that of the down-pumping P-4. This result is well-known from previous solids suspension studies (Corpstein et al., 1994). In the up-pumping mode, the just-suspended power of the P-4 is typically lower than that of the HE-3. The just-suspended powers in the up-pumping mode are significantly greater than those in the down-pumping mode except at large impeller diameter to tank diameter ratios. The lowest just-suspended powers in the up-pumping mode (those at $D/T = 0.55$) are greater than the lowest just-suspended powers in the down-pumping mode (those at $D/T = 0.34$); however, in the dish-bottom vessel, the lowest just-suspended powers in the up-pumping mode are comparable to the lowest just-suspended powers in the down-pumping mode.

It is interesting to compare the results for the flat and dish-bottom vessels as shown in Figure 8 which presents the ratio of the just-suspended torque in the flat-bottom vessel to the just-suspended torque in the dish-bottom vessel (plots of the just-suspended power ratios are similar). In the down-pumping mode (with all reported data taken at $C/T = 0.25$), the just-suspended torque requirements of both the HE-3 and P-4 impellers are slightly higher in the flat-bottom vessel than in the dish-bottom vessel for the smaller impeller diameter

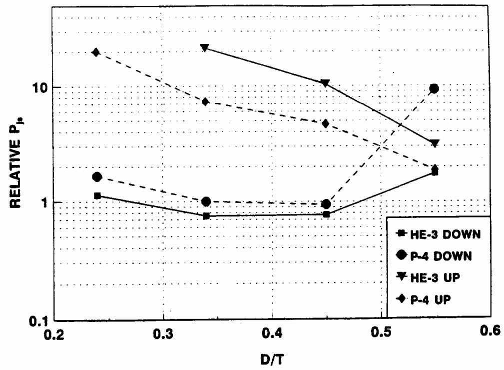

Figure 7a

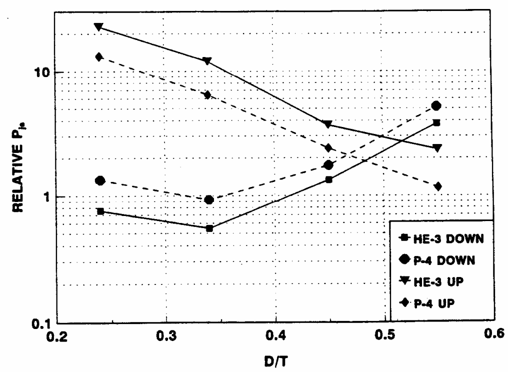

Figure 7b

Figure 7 — Comparison of relative just-suspended power requirements in flat-bottom (a) and dish-bottom (b) vessels ($C/T = 0.25$).

to tank diameter ratios ($D/T = 0.24$ and 0.34). At larger impeller diameter to tank diameter ratios ($D/T = 0.45$ for both impellers and $D/T = 0.55$ for the HE-3 only), the just-suspended torque requirements are lower in the flat-bottom vessel. This is due to the low fluid velocities that occur at the vessel center beneath larger impellers, combined with the tendency of the solids to settle at the lowest point on the base of the dish. In flat-bottom vessels, the fluid velocities are also low at the vessel center with larger impellers, but the settled solids are spread more evenly over the vessel base. For the largest impeller diameter to tank diameter ratio ($D/T = 0.55$), flow reversal occurs for the down-pumping P-4 impeller, greatly increasing the just-suspended torque requirements in both the flat and dish-bottom vessels (Myers et al., 1996). However, the increase in just-suspended torque is more significant in the flat-bottom vessel than in the dish-bottom vessel. Since flow reversal does not occur for the HE-3 impeller at this impeller diameter to tank diameter ratio, the just-suspended torque requirement remains lower in the flat-bottom vessel.

In the up-pumping mode, the just-suspended torque requirements of both the HE-3 and P-4 impellers are always higher in the flat-bottom vessel (refer to Figure 8), averaging about 37% higher. The higher just-suspended torques (and powers) in the flat-bottom vessel in the up-pumping mode are due to the difficulty that an up-pumping impeller has suspending the solids at the periphery of the vessel. As

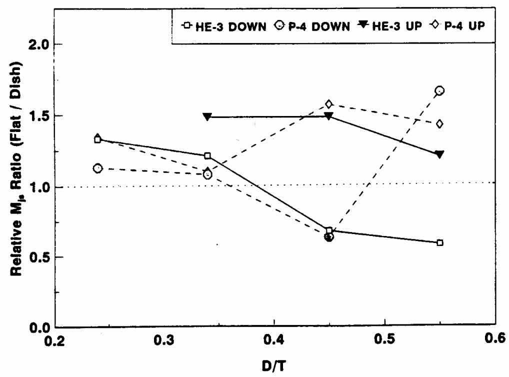

Figure 8 — Just-suspended torque ratios of up-pumping and down-pumping impellers (ratios are flat-bottom vessel relative to dish-bottom vessel).

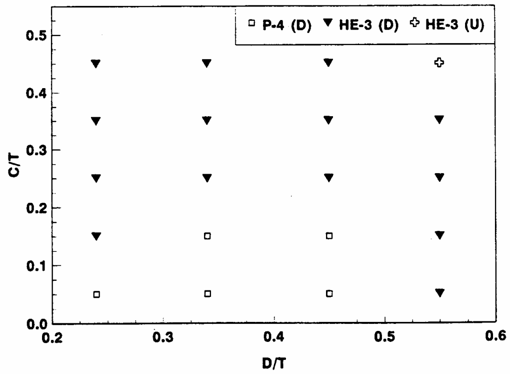

Figure 9a

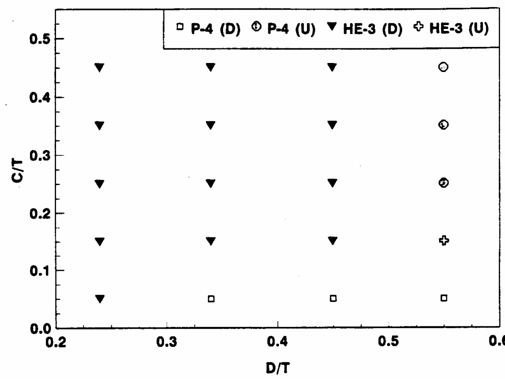

Figure 9b

Figure 9 — Impeller selection guidelines for just-suspended power minimization in flat-bottom (a) and dish-bottom (b) vessels. Data points indicate the impeller with the lowest just-suspended power requirements at a particular *D/T*-*C/T* combination. (D) indicates the down-pumping mode and (U) indicates the up-pumping mode.

shown in Figure 1, the velocities around the vessel periphery are very low when the up-pumping mode is used. In a flat-bottom vessel, solids settle in this region and are difficult to suspend. In a dish-bottom vessel, settled solids accumulate at the central, deepest point on the vessel base rather than around the vessel periphery. Since the fluid velocities produced by an up-pumping impeller are higher in this region than at the vessel periphery (refer to Figure 1), just-suspended speed, torque, and power requirements of up-pumping impellers are lower in dish-bottom vessels than in flat-bottom vessels.

In general, the fluid velocities across the entire vessel base are low for the up-pumping mode of operation because the vessel base is on the suction side of the impeller. While the impeller discharge velocities are high for the up-pumping mode, these velocities are directed away from the settled solids on the vessel base. Conversely, in the down-pumping mode, the highest fluid velocities are directed at the vessel base (refer to Figure 1d). Because of the upwards orientation of its high-velocity discharge, the up-pumping mode of operation typically disperses the solids throughout the entire batch at just-suspended conditions (when $Z/T = 1$). Conversely, the down-pumping mode of operation often disperses the solid throughout less of the batch at just-suspended conditions (Hicks et al., 1997).

Impeller selection guidelines

The results presented here can be generalized in terms of impeller selection guidelines for a particular system geometry (*D/T*-*C/T* combination). When choosing between up-pumping and down-pumping P-4 impellers, the up-pumping mode should be used only at the largest impeller diameter to tank diameter ratio ($D/T = 0.55$). This recommendation holds for both flat and dish-bottom vessels at all impeller off-bottom clearances studied ($0.05 \leq C/T \leq 0.45$) and is based on minimization of the just-suspended speed, torque, and power requirements. The same guideline holds for the HE-3 in dish-bottom vessels, but the down-pumping mode should always be used for an HE-3 impeller in flat-bottom vessels.

When choosing between P-4 and HE-3 impellers in both the up and down-pumping modes, the selection procedure is more complex. Use of the P-4 impeller minimizes the just-suspended speed in both flat and dish-bottom vessels, with the up-pumping mode recommended only for the largest impeller diameter to tank diameter ratio ($D/T = 0.55$). Selection of the HE-3 impeller minimizes just-suspended torque, with the up-pumping mode recommended only at the largest impeller diameter to tank diameter ratio in dish-bottom vessels. A down-pumping HE-3 is always recommended for torque minimization in flat-bottom vessels.

The minimum just-suspended power requirements determined during this work are presented in Figure 9. In the flat-bottom vessel (Figure 9a), the down-pumping HE-3 is generally preferred except at low off-bottom clearances where the just-suspended power requirements of the P-4 impeller are approximately 5% lower (given the accuracy of determining just-suspended power requirements, the down-pumping P-4 and HE-3 power requirements are essentially identical for these geometries). The only instance in which the up-pumping mode minimizes just-suspended power is with the HE-3 impeller at the combination of the largest impeller diameter to tank diameter ratio at the largest impeller off-bottom clearance ($D/T = 0.55$ at $C/T = 0.45$). The situation in the dish-bottom vessel is similar (Figure 9b), but the up-pumping mode is preferred at the largest impeller diameter to tank diameter ratio (except at the lowest impeller off-bottom clearance, C/T = 0.05). For these geometries (D/T = 0.55 at $C/T \geq 0.15$), the performance of the recommended up-pumping impeller is much better than that of the down-pumping mode, with the up-pumping just-suspended power requirements being only about 30% of the down-pumping power requirements (refer to Figure 7). In general, the up-pumping P-4 performance is similar to or better than that of the up-pumping HE-3 for these geometries.

Concluding remarks

The just-suspended speeds of up-pumping pitched-blade and high-efficiency impellers have been correlated as functions of geometry (D/T and C/T) in both flat and dish-bottom vessels using two design correlations. The associated just-suspended torque and power requirements of up-pumping pitched-blade and high-efficiency impellers are minimized at low impeller off-bottom clearances and large impeller diameter to tank diameter ratios. In general, the just-suspended torque and power requirements of up-pumping pitched-blade and high-efficiency impellers are substantially higher than those of the down-pumping mode. However, if a large impeller diameter is required to avoid critical speed limitations or to achieve sufficient power inputs at high solids loadings, then up-pumping impellers may be a viable option.

Acknowledgement

The assistance of Kevin M. Wiwi in performing the power number and preliminary solids suspension experiments is gratefully recognized.

Nomenclature

B	= Zwietering (1958) solids loading factor (solids mass/liquid mass)
C	= impeller off-bottom clearance (measured from the lowest point on the impeller to the lowest point on the vessel base), m
d_p	= particle diameter, m
D	= impeller diameter, m
$f(D/T,C/T)$	= $N_{js}(D/T,C/T)/N_{js}(D/T = 0.35, C/T = 0.25)$; geometric factor of the just- suspended speed correlation of Corpstein et al.(1994), dimensionless
$f(X)$	= $N_{js}(X)/N_{js}(X = 0.05)$; solids loading factor of the just-suspended speed correlation of Corpstein et al. (1994), dimensionless
g	= gravitational acceleration, m/s^2
k	= impeller constant of the just-suspended speed correlation of Corpstein et al. (1994)
M	= impeller torque, N·m
N	= impeller rotational speed, s^{-1} (rev/s)
N_{js}	= just-suspended speed, s^{-1} (rev/s)
N_p	= impeller power number ($P/\rho N^3 D^5$), dimensionless
n	= scaleup exponent, dimensionless
P	= impeller power draw, W
S	= Zwietering (1958) factor defined in Equation 2, dimensionless
T	= vessel diameter, m
T_o	= reference vessel diameter, 0.29 m
u_t	= terminal settling velocity of a single particle in quiescent liquid, m/s
W	= impeller blade width (actual, not projected), m
X	= solids loading (solids mass/slurry mass), dimensionless
Z	= slurry height, m

Greek letters

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

Subscripts

js	= refers to just-suspended conditions
l	= refers to liquid
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