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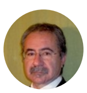

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Power Consumption in Agitated Vessels Provided with Multiple-Disk Turbines

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The power dissipated by one-, two-, or three-disk turbines (Rushton type) in stirred vessels was experimentally determined under turbulent conditions. The power dissipated by each individual impeller (in single- or multiple-impeller configurations) and the total power consumption were measured by means of strain gauges mounted on the shaft and were reported as individual or total power numbers. Results were obtained for different combinations of number of impellers, off-bottom clearance of the lowest impeller, and spacing among impellers. These variables were found to play a very important role in the power drawn by individual impellers and, hence, the total power consumption. The impeller closest to the vessel bottom generally consumed significantly less power than the other impeller(s). This was especially true for combinations of low impeller clearances and small impeller spacing. Proximity of two impellers also lowered their power consumption. Only when the impellers were significantly spaced apart and the lowest impeller sufficiently distant from the vessel bottom did each individual impeller draw a power approaching that of a single-impeller configuration. The results of this work can be used to predict the power consumed by individual impellers in multiple-impeller systems and therefore to help scale-up processes (such as those dominated by different local mass-transfer coefficients in different parts of the vessel) in which knowledge of the local power dissipation may be critical.

Introduction

Mixing in stirred vessels is an extremely common operation in industrial practice. The power dissipated by the agitation system is fundamental to any mixing process since energy is needed to homogenize the vessel content, disperse immiscible phases, suspend solids, increase mass transfer, and, in general, produce the desired mixing effect.

Power consumption depends not only on the type of impeller(s) used, the agitation speed, and the physical properties of fluid but also on the geometry of the system, including the number and location of the impellers in the mixing vessel. A significant amount of data can be found in the literature on power consumption in single-impeller systems. However, only incomplete information is available for power consumption in mixing tanks provided with multiple impellers, although their industrial importance is significant. In particular, very little information is available on the power dissipated by each individual impeller in multiple-impeller systems. The power consumed by multiple impellers and the characteristics of the flow that they generate are often estimated on the basis of the power consumed by single impellers. This is not correct in many applications.

Therefore, the main objective of this study was to experimentally determine the power dissipated by individual disk turbines (in single- or multiple-impeller configurations) in mixing vessels, as well as the total power consumed by the whole agitation system, as a function of different combinations of number of disk turbines, off-bottom clearance of the lowest impeller, and spacing among impellers.

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Literature Survey

Single-Disk Turbine Systems. Agitation systems with a single-disk turbine (DT) have been studied extensively, especially using low-viscosity fluids in vessels for which $H/T = 1$ (Hudcova et al., 1989). Many investigators (Rushton et al., 1950; Bates et al., 1963, 1966; Gray et al., 1982; Shiue and Wong, 1982; Chudacek, 1985) have experimentally determined the power characteristics of single impellers and have found that the impeller power number, *Ne*, reaches a constant value for a given geometry if the agitation intensity is high enough to produce turbulent flow ($Re > 10\,000$). Rushton et al. (1950) found that, for the case in which $D/T = {}^1/_3$, $H/T = 1$, $C'_1/T = 1$, and $B/T = {}^1/_{10}$, *Ne* for DTs was 6.3. They also reported that the impeller off-bottom clearance had no effect if the value of C'_1/D ranged from 0.7 to 1.6. No effect of liquid height was found. Bates et al. (1963) produced $Ne-Re$ plots under the conditions $D/T = {}^1/_3$, $C'_1/T = {}^1/_3$, and $H/T = 1$. The values of *Ne* that they reported for DTs were 4.8 and 5.0 for systems with four $T/12$ baffles and four $T/10$ baffles, respectively. Their measurements showed that the impeller off-bottom clearance has a definite effect on power consumption. Gray et al. (1982) proposed a power correlation for DTs: for $C'_1/D > 1.1$, they found a constant power number of 5.17, while for $C'_1/D < 1.1$, *Ne* varied with $(C'_1/D)^{0.29}$. The effect of baffling was found to be negligible for ${}^1/_{12} \le B/T \le {}^1/_{10}$. The effect of D/T was small under these conditions. Raghava Rao and Joshi (1988) found the power number to be 5.18 and 4.40 for clearances of $T/3$ and $T/6$, respectively. Rewatkar et al. (1990) found that $Ne = 5.18$ ($D/T = {}^1/_3$; C'_1/D

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= 1). *Ne* was observed to decrease with decreasing clearance. However, *Ne* decreased when the clearance was more than $T/4$ because of surface aeration. Without surface aeration, the liquid height was found to have little effect on power consumption.

Multiple-Disk Turbine Systems. Bates et al. (1963) determined the power consumption of dual impellers, although not DTs. They found that dual 45° pitched-blade turbines (PBTs) did not consume twice the power of a single PBT, if $S/D < 4$. Dual flat-blade turbines (FBT) consumed a total power of almost 25% greater than the sum of two single ones, when $S/D < 1$.

Nienow and Lilly (1979) found that *Ne* for a single DT was 4.9 while that for the two was 10.2 ($S/D = 2$). They pointed out that *Ne* for *n* impellers was approximately *n* times that for a single impeller provided that $S/D \geq 1$. Kuboi and Nienow (1982) found that in double-DT systems ($H/T = 1$) the power numbers for the lower impeller, the upper impeller, and the combined system were respectively 3.6, 3.9, and 7.5.

Roustan (1985) measured power numbers of 10.4 and 14.2, in vessels with hemispherical bottoms provided with two or three DTs, respectively. Machon et al. (1985) studied mixed dual-impeller configurations, i.e., a DT used in combination with a PBT (pumping upward or downward). They found that the total power was less than the sum of the powers of the individual impellers when the two impellers were spaced at a distance approaching the impeller diameter. For $S/D = 1$, the resulting *Ne* equaled the sum of the power numbers of the two impellers, although the impellers were of different types.

Smith et al. (1987) confirmed that the power consumed by two impellers in tall vessels ($H/T = 3$) was twice that of a single impeller, if $S/D = 2$. In evenly spaced ($S/D = 2.5$) triple-DT systems, the total power was 2.98 times that of a single DT. For $S/D < 0.75$ the power consumed by the multiple-impeller system was only a fraction of the sum of those dissipated by an equal number of single impellers. For $1 < S/D < 1.5$, the power demand increased steeply, and when $S/D = 1.5$, it was more that 90% of the value obtained with an equal number of single impellers. Bujalski et al. (1987) showed that geometric parameters such as the thickness of the disk and the impeller blades can have an appreciable effect on power number. Abrardi et al. (1988) found that the power dissipated by two impellers with $S/D = 2$ and $C'_1/D = 1$ was twice that of a single impeller. Nocentini et al. (1988) reported a power number of 18.5 for a four-impeller system and 4.6 for a single-impeller system. They also found that power numbers were unaffected by liquid height.

Hudcova et al. (1989) measured *Ne* for one and two DTs with $D/T = {}^1/_3$, $H/T = 1$ or 2, $C'_1/T = {}^1/_3$, and S/D in the range 0.2−3. When the impellers were touching ($S/D = 0.2$), the power drawn was 1.29 times that of a single impeller. For $0.5 < S/D < \sim 1.5$, one circulation loop for each impeller was observed, and the power consumption was 1.54−1.91 times that of a single impeller. For $S/D > \sim 2$, each impeller developed its typical radial flow pattern and the power drawn approximated twice that of a single one.

Abrardi et al. (1990) reported that the power dissipated by a multiple-impeller system was the sum of that dissipated by single impellers, if S/D was in the range 1.5−2. Chiampo et al. (1991) studied the effect of *S* on power for dual DTs ($0.2 < S/D < 4$, $C'_1/D = 1$), in which the height of the liquid above the upper impeller was kept constant while the liquid height was varied. They found that the power drawn increased moderately with spacing up to $S/D = 0.6$ and slightly when $0.6 < S/D < 1.3$. For $S/D > 1.3$ the zone between two impellers became turbulent and a steep increase in power drawn was observed. At high speeds (>450 rpm), the power drawn was approximately twice that of a single impeller for $S/D \geq 1.6$, while at low speeds the same occurred only when $S/D \geq 1.9$.

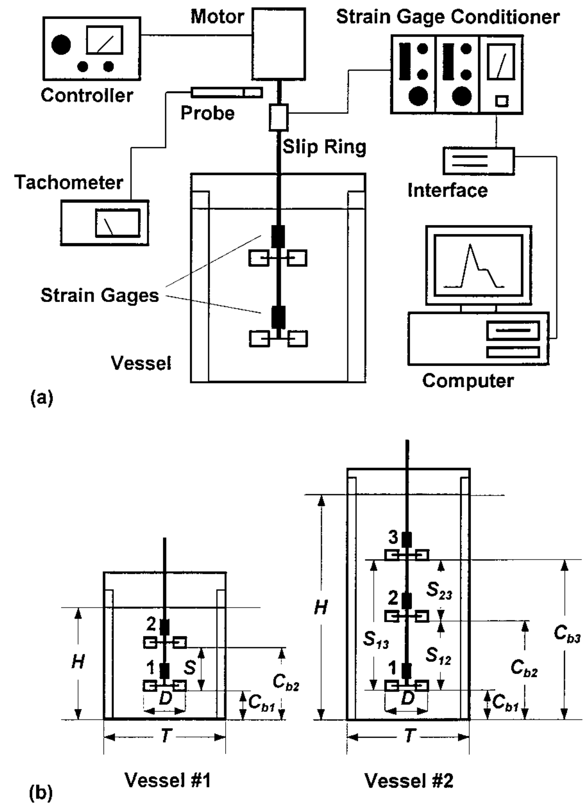

Figure 1. Experimental setup: (a) experimental apparatus; (b) vessels used in this work: vessel 1 ($H/T = 1$; $B/T = 0.1$); vessel 2 ($H/T = 2$; $B/T = 0.088$).

Lu and Yao (1991) reported that the total power consumption of a three-impeller system was about 3 times that of a single impeller (for which $Ne = 4.5$), but that the individual *Ne* values of top, middle, and bottom impellers were different (5.05, 5.5, and 3.75, respectively). Armenante and Uehara Nagamine (1997) studied solid suspension and power consumption in single- and double-DT systems for the case in which the lower impeller was very close to the vessel bottom (${}^1/_{48} < C_{b1}/T < {}^1/_{16}$). They found that the lower impeller consumed only a fraction (28−31%) of the total power drawn.

Experimental Apparatus

The experimental setup is shown in Figure 1a. Two open, flat-bottomed, cylindrical, Plexiglas vessels with four baffles spaced 90° apart and different liquid height-to-tank diameter ratios were used (Figure 1b). Table 1 gives the vessel dimensions. Agitation was provided by a 2.0 hp variable speed motor (G. K. Heller Corp.) with a maximum speed of 1800 rpm. The rotational speed was measured using a digital tachometer with a photoelectric pick-up sensor (Cole Parmer), accurate within ±1 rpm.

Table 1. Dimensions of Vessels

vessel no.	vessel diameter, T (m)	vessel height (m)	liquid height, H (m)	H/T	baffle width, B (m)	B/T (%)
1	0.289	0.386	0.289	1	0.286	10
2	0.289	0.688	0.578	2	0.254	8.8

Table 2. Shaft Lengths and Strain Gauge Locations

		distance of each strain gauge from the bottom of the shaft (m)		
shaft no.	shaft length (m)	bottom gauge	middle gauge	top gauge
1	0.61	0.073		0.26
2	0.838	0.03	0.34	0.49

Six-blade disk turbines (Rushton type) having diameters equal to 0.0635, 0.0763, and 0.102 m, respectively, were used as impellers (blade height-to-impeller diameter ratio, $^1/_5$; blade width-to-impeller diameter ratio, $^1/_4$; disk diameter-to-impeller diameter ratio, $^3/_4$). The thicknesses of the disks were 1.6, 1.6, and 2.0 mm, respectively (corresponding to disk thickness-to-impeller diameter ratios equal to 0.0245, 0.0210, and 0.0197, respectively). Depending on the experiment, one, two, or three impellers were mounted on the shaft. All the DTs used in any single experiment had the same diameter.

The shafts consisted of hollow aluminum tubes having an o.d. of 9.5 mm, a wall thickness of 1.65 mm, and either two or three strain gauges (Measurements Group Co., CEA-06-187UV-350). The shaft characteristics are given in Table 2. Shafts 1 and 2 were used with vessels 1 and 2, respectively. Before permanently attaching the strain gauges to the shafts, 25.4-mm-long metal collars having an internal diameter equal to the o.d. of the shaft and an external diameter equal to the bore diameter of impellers (12.7 mm) were slid onto the shaft between the points where the strain gauges were to be positioned. The impellers were then mounted on the collars with set screws. This arrangement enabled the impellers to be slid onto the shaft without touching the protruding strain gauges and to move the impeller–collar assemblies along the shaft, so that the distances, S_{ij}, between the impellers could be varied. The strain gauges were connected with insulated lead wires passing through the hollow core of the shaft to a slip ring assembly (Airflyte Electronics Co., Bayonne, NJ, Part No. CAY1030-12-2) externally connected to a signal conditioner and amplifier system (2120A system, Measurement Group Co.). A data acquisition system (Labtech Notebook) connected to a computer was used to analyze all the signals and extract the data, as explained below.

The vessel could be translated vertically to vary the position of the impeller–shaft assembly relative to the vessel (and especially the off-bottom impeller clearance of the lowest impeller, C_{b1}, measured from the bottom of the disk blade). Single-impeller experiments were carried out in vessels 1 and 2. Double- and triple-impeller runs were conducted respectively in vessels 1 and 2. In the latter case the spacing between the top and bottom impellers (S_{13}) was kept constant, while the position of the middle impeller was varied. All experiments were performed at room temperature using tap water. Its physical properties were taken at 19 °C (Machon et al., 1985).

Data Collection and Calibration Procedure

Each strain gauge produced a signal, Φ_i (in millivolts), directly proportional to the cumulative torque, $\tau_{\text{gauge } i}$, applied to the gauge by all the impellers below it. The power drawn by each impeller, P_i, was calculated from the torque applied to each impeller, τ_i, and the agitation speed N (in revolutions per second), as follows:

$$P_i = \omega\tau_i = 2\pi N(\tau_{\text{gauge } i} - \tau_{\text{gauge } i-1}) = 2\pi N(k_{\text{gauge } i}\Phi_{\text{gauge } i} - k_{\text{gauge } i-1}\Phi_{\text{gauge } i-1}) \quad (1)$$

The corresponding Newton number (power number) for each impeller, Ne_i, was calculated from (Rushton et al., 1950):

$$Ne_i = P_i/\rho N^3 D^5 \quad (2)$$

The impeller Reynolds number was defined as $Re = \rho ND^2/\mu^2$.

The data acquisition system received the gauge signals from the strain gauge conditioner and the agitation speed signal from the tachometer and calculated, on line, the values of N, τ_i, P_i, Ne_i, and Re for each impeller. The sampling frequency of the data acquisition system was 30 min^{-1}. The value of each experimental variable was determined by calculating the average of the 30 readings obtained during a 60-s sampling time.

All experiments were run in duplicate at agitation speeds of 6.67 and 8.33 rps, respectively (400 and 500 rpm), corresponding to Re in the range 26 000–83 000 (fully turbulent regime). The difference between Ne calculated at the two agitation speeds never exceeded 4.3% of the average value. The results were interpreted assuming that

$$P_i = f(N,D,\rho,\mu,T,H,D,C_{b1},S_{12},S_{23},n) \quad (3)$$

which can be rearranged as

$$Ne_i = f\left(\frac{C_{b1}}{D},\frac{T}{D},\frac{S_{12}}{D},\frac{S_{23}}{D},n\right) \quad (4)$$

when the following assumptions are made: (1) Ne is not a function of the Reynolds number in the turbulent region; (2) Ne is not a function of the Froude number because of full baffling (Bates et al., 1966); (3) Ne is independent of the height of the liquid if the liquid level above the impeller is sufficiently high (typically larger than D); (4) Ne is independent of baffling if full baffling conditions are maintained. The last two assumptions were tested here for the case of a single impeller (as shown in the Results and Discussion section).

The system was periodically calibrated by disconnecting the shaft from the motor and placing it horizontally on supports. The gauge under exam was in the cantilevered section of the shaft. Torques of known intensities were applied to the shaft, and the gauge signal was measured as usual. τ–Φ calibration curves were constructed and found to be linear, so that the proportionality factors $k_{\text{gauge } i}$ could be determined. The reproducibility of the data was within ± 5.2% for all $k_{\text{gauge } i}$. No significant changes in the calibration curves were observed over time. The distance, L_{G-I}, between an

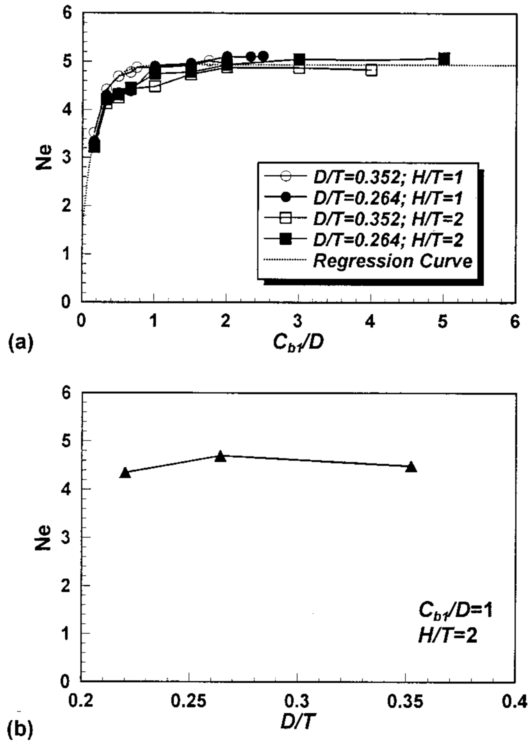

Figure 2. Single-impeller system: (a) effect of C_{b1}/D ratio on power number; (b) effect of D/T ratio on power number.

impeller and the strain gauge above it was found to have no effect on power measurement.

Results and Discussion

Single-Impeller Systems. In turbulent regime Ne has been reported to be constant (Bates et al., 1963), implying, from eq 2, that $P \propto N^3$. From a regression of the $Ne-N$ data obtained here the exponent of N was found to be 3.01 (vessel 1; $D/T = 0.264$; $C_{b1}/D = 1$; $H/T = 1$), 3.01 (vessel 2; $D/T = 0.264$; $C_{b1}/D = 1$; $H/T = 2$), and 2.95 (vessel 2; $D/T = 0.352$; $C_{b1}/D = 1$; $H/T = 2$).

The effect of off-bottom clearance on Ne is shown in Figure 2a. At low clearance ($C_{b1}/D = 0.16$), the bottom circulation of disk turbines was reduced, resulting in a low power consumption. A small increase in C_{b1}/D (from 0.16 to 0.33), produced a steep increase in power number. For $0.33 < C_{b1}/D < 1$, a moderate increase in power number was observed, possibly caused by the establishment of a transition flow pattern around the impeller. In this range the curves showed the most significant deviations from one another. For higher C_{b1}/D values a fully developed "double-eight" flow pattern was established (Armenante and Uehara Nagamine, 1997). For $C_{b1}/D > 1.75$, Ne approached its asymptotic value in the range 4.9−5.1, depending on the curve. This value is in agreement with the most acceptable literature value of 5.0 at standard conditions (Kuboi and Nienow, 1982). The following function was used to interpolate the data:

$$\frac{Ne_{\max} - Ne}{Ne_{\max} - Ne_{\min}} = \exp\left(-a\frac{C_{b1}}{D}\right) = \exp\left[-a\left(\frac{C'_1}{D} - \frac{w_b}{2D}\right)\right] \tag{5}$$

where $Ne_{\max}$ and $Ne_{\min}$ are respectively the asymptotic value of the power number for $C_{b1}/D \rightarrow \infty$, and the value of the power number at $C_{b1}/D = 0$ (corresponding to $C'_1/D = w_b/(2D)$, i.e., the lowest possible position of the impeller). A nonlinear regression analysis for the first data set ($D/T = 0.352$ and $H/T = 1$) yielded the following expression:

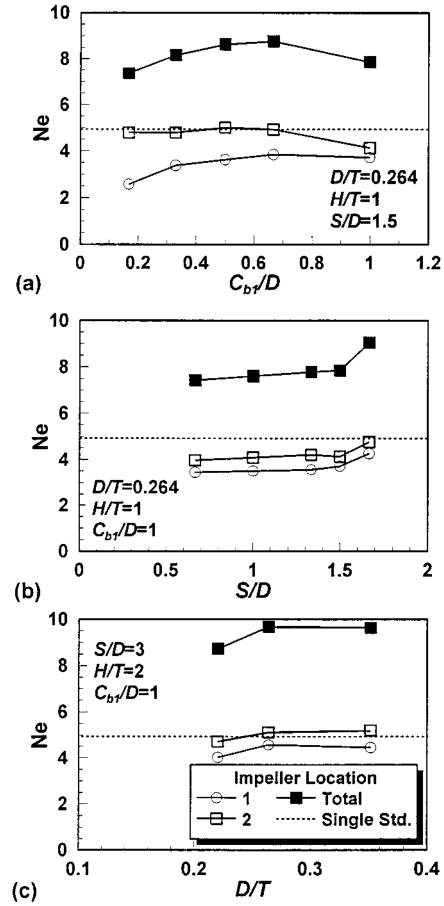

Figure 3. Double-impeller system: power numbers of individual impellers and total power number (equal to the sum of the power numbers of the individual impellers) as a function of (a) C_{b1}/D ratio, (b) S/D ratio, and (c) D/T ratio.

$$Ne = 4.93 - 3.44\exp\left(-5.38\frac{C_{b1}}{D}\right) = 4.93 - 3.44\exp\left[-5.38\left(\frac{C'_1}{D} - \frac{w_b}{2D}\right)\right] \tag{6}$$

which is also plotted in Figure 2a. From this equation Ne at $C_{b1}/D = 1$, $D/T = 0.352$, and $H/T = 1$ (taken here as the "standard conditions") was found to be 4.92. This value was taken here to be the value of Ne for a single impeller at standard conditions ($Ne_{\text{Single Std.}}$). This number is very close to the commonly reported value of 5 (difference = 1.7%). Furthermore, this value is in excellent agreement with the very accurate power number of 4.87 reported by Bujalski et al. (1987) for a system geometrically similar to that used in this work and having an impeller with a disk thickness-to-impeller diameter ratio equal to 0.0167 (compared to 0.0197 in this work). The disk thickness has been shown by Bujalski et al. (1987) to have a significant impact on Ne and may be one of the reasons for the discrepancies in power numbers reported by different investigators.

The liquid height was found here to have a negligible effect on power consumption (Figure 2a), if there is no surface aeration or air entrainment (Rushton et al., 1950; Rewatkar et al., 1990). These data also indicate

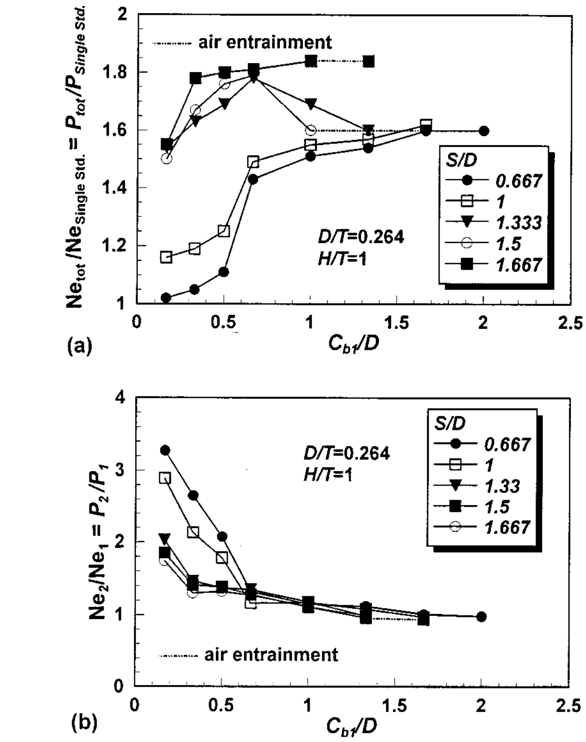

Figure 4. Double-impeller system: (a) effect of C_{b1}/D ratio on the ratio of total power number (equal to the sum of the power numbers of the individual impellers) to the power number of a single impeller in the standard position ($C_{b1}/D = 1$, $Ne_{\text{Single Std.}} = 4.92$); (b) effect of C_{b1}/D ratio on the ratio of the power number of the upper impeller (2) to that of the lower impeller (1).

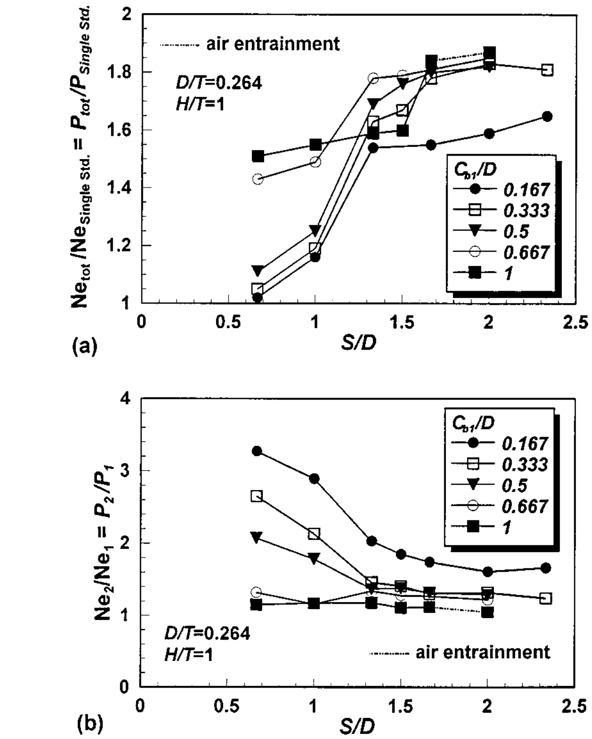

Figure 5. Double-impeller system: (a) effect of S/D ratio on the ratio of total power number (equal to the sum of the power numbers of the individual impellers) to the power number of a single impeller in the standard position ($C_{b1}/D = 1$, $Ne_{\text{Single Std.}} = 4.92$); (b) effect of S/D ratio on the ratio of the power number of the upper impeller (2) to that of the lower impeller (1).

that the extent of baffling (B/T ratio equal to 10% and 8.8% for vessels 1 and 2, respectively) had a minor effect on Ne once fully baffled conditions were achieved (Gray *et al.*, 1982). The effect of the D/T ratio on Ne was small, at least in the D/T range tested here (Figure 2b).

Double-Impeller Systems. In Figure 3a the effect of C_{b1} on individual power numbers is shown. Because of the appreciable impeller spacing ($S/D = 1.5$), Ne for the upper impeller was nearly independent of the lower impeller and very similar to that for a single impeller under standard conditions. The drop in Ne_2 for C_{b1}/D approaching 1 can be attributed to the reduced distance between the upper impeller and the free surface, resulting in a reduced circulation above the upper impeller. At low impeller clearances Ne_1 was much lower than $Ne_{\text{Single Std.}}$. Even as C_{b1}/D increases Ne_1 did not reach $Ne_{\text{Single Std.}}$. This resulted in a total Ne value smaller than the sum of those for two single impellers. This is in agreement with the recent results of Armenante and Uehara Nagamine (1997), who also measured low power numbers (especially low Ne_1 values) when the impeller clearance was very small.

The effect of S is shown in Figure 3b. For $S/D < 1.5$ both impellers had individual power numbers significantly smaller that $Ne_{\text{Single Std.}}$, although the upper impeller always dissipated more power than the lower impeller. When $S/D > 1.5$, each impeller operates similarly to a single one, and the individual and total Ne values increase more rapidly. The power number appeared to be only a weak function of the impeller diameter (Figure 3c). Also in this case, the lower impeller always consumed less power than the upper impeller.

The effect of C_{b1} on power consumption was obtained for various S/D values, as shown in Figure 4a,b. The data presented in this figure can be used to determine the individual and total power numbers for any double-disk turbine system for which $H/T = 1$. When $S/D \leq 1$, Ne_{tot} increased with C_{b1}, similarly to the single-impeller case. It is interesting to note that at very low clearances of the lower impeller ($C_{b1}/D \leq 0.5$) the total power drawn by a double-impeller system having $S/D \leq 1$ is about the same or slightly higher (up to 25%) than that of a single impeller at standard conditions (Figure 4a). This means that the addition of a second, properly positioned impeller near the vessel bottom (the so-called “tickler impeller”) to a “standard” single impeller results in only a relatively small power increase. This energy efficiency is reduced when $S/D \geq 1.33$.

A steep increase in Ne_{tot} was observed in the range $0.5 < C_{b1}/D < 0.667$, when $S/D \leq 1$. As shown in Figure 4b, the Ne_2/Ne_1 ratio decreased sharply for $C_{b1}/D < 0.667$, with the upper impeller drawing much more power than the lower one. Such a decrease in Ne_2/Ne_1 was caused primarily by an increase in the power drawn by the lower impeller.

Somewhat unexpected results were obtained in the range $1.33 \leq S/D \leq 1.5$. Ne_{tot} increased with the impeller clearance up to $C_{b1}/D = 0.667$ ($Ne_{\text{tot}}/Ne_{\text{Single Std.}} = 1.79$). However, contrary to the single-impeller case, a decrease in Ne_{tot} was observed when C_{b1}/D went from 0.667 to 1 ($Ne_{\text{tot}}/Ne_{\text{Single Std.}} = 1.6$). Duplicate experiments conducted independently under the same conditions confirmed this observation. This phenomenon can be attributed to a change in the hydrodynamic regime caused by small changes in the distance between impellers. When S was further increased ($S/D \geq 1.667$), no reduction in Ne_{tot} was found in the range of clearances examined. A comparison between parts a and b of Figure 4 shows that for $C_{b1}/D > 1$ the power

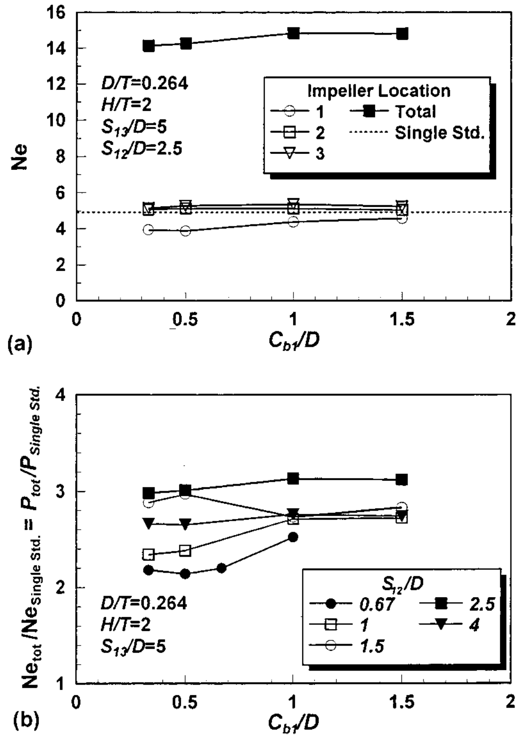

Figure 6. Triple-impeller system: (a) power numbers of individual impellers and total power number (equal to the sum of the power numbers of the individual impellers) as a function of C_{b1}/D ratio; (b) effect of C_{b1}/D ratio on the ratio of total power number (equal to the sum of the power numbers of the individual impellers) to the power number of a single impeller in the standard position ($C_{b1}/D = 1$, $Ne_{\text{Single Std.}} = 4.92$).

dissipated by the lower impeller was similar to that of the upper impeller, although the individual (as well as total) powers drawn varied with C_{b1}/D.

The power data reported in Figure 5a,b as a function of S/D using C_{b1}/D as the parameter also show that power dissipation is strongly affected by impeller spacing and that the effect is more pronounced at low clearance. In general, the power consumption increased when spacing was increased. At low clearance ($C_{b1}/D \leq 0.667$), a steep increase in Ne_{tot} was observed for $1 < S/D < 1.667$, while a moderate increase was noted when $S/D < 1$ or $S/D > 1.33$. When S is increased, the amount of liquid between the impellers increases linearly with S. If the impellers are close enough to prevent a full double-eight flow regime from existing around each impeller, the mass of liquid between the impellers tends to rotate as a solid body, thus increasing the power drawn by the impellers as S is increased, as found here. This observation is in line with those of previous investigators (Chiampo et al., 1991). A sharp increase in Ne_{tot} was found when $1.5 < S/D < 1.667$, with a $Ne_{tot}/Ne_{\text{Single Std.}}$ value of 1.84 at $S/D = 1.667$. This effect is likely caused by the change in flow pattern (Mahmoudi and Yianneskis, 1991).

From the available literature data it appears that double-disk turbines draw a total power twice as large as that of a single-DT system only if the spacing is large, i.e., $S/D > 1.5$ or 2 (Abrardi et al., 1990; Chiampo et al., 1991). In this work, air entrainment from the free surface prevented to carry out experiments at $C_{b1}/D = 1$ and $S/D \geq 2$. However, the results obtained indicate that when $S/D = 1.677$, the power dissipated by two disk turbines was not twice that of the single one (Figure 5a), probably because of the small distance

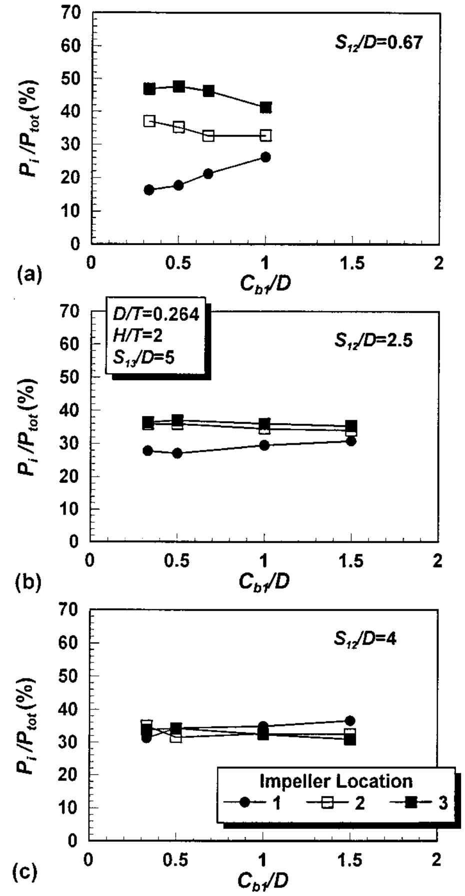

Figure 7. Triple-impeller system: ratio of power consumed by individual impellers to total power consumption as a function of C_{b1}/D: (a) $S_{12}/D = 0.67$; (b) $S_{12}/D = 2.5$; (c) $S_{12}/D = 4$.

(about one impeller diameter) between the higher impeller and the free surface.

The power dissipated by each individual impeller was found to be a strong function of spacing (Figure 5b). This effect was more evident when the impeller clearance was small. When $C_{b1}/D < 0.677$, the Ne_2/Ne_1 ratio dropped sharply with S for $S/D < 1.5$. This variation was caused primarily by a significant increase in Ne_1 with increasing S. For $C_{b1}/D \geq 0.667$, this effect was not appreciable and Ne_2/Ne_1 approached the value of 1.

Triple-Impeller Systems. A plot of Ne as a function of C_{b1}/D, reporting both individual (for each impeller) and cumulative (total) Ne values, is given in Figure 6a. Since the middle impeller was placed midway between the other two impellers and the impeller spacing was large ($S_{12}/D = S_{23}/D = 2.5$), the middle and upper impellers had power numbers similar to that of the single standard impeller case. Ne for the lower impeller was smaller than for the other two, especially at low C_{b1}/D values. The increase in Ne_{tot} with clearance resulted almost exclusively from the increase in Ne_1. The effect of off-bottom clearance on Ne_{tot} is shown in Figure 6b. The C_{b1} effect was pronounced when the middle impeller was close to the lower impeller. Ne_{tot} increased with clearance but decreased with C_{b1}/D for $0.5 < C_{b1}/D < 1$ and $S_{12}/D = 1.5$. A similar trend was also observed in the double-DT systems.

Figure 7 shows the effect of C_{b1}/D on the fractional power consumption of each individual impeller, P_i/P_{tot}. When S_{12}/D was small, significant differences in power consumption among impellers were observed, especially at low C_{b1}/D values (Figure 7a). These differences

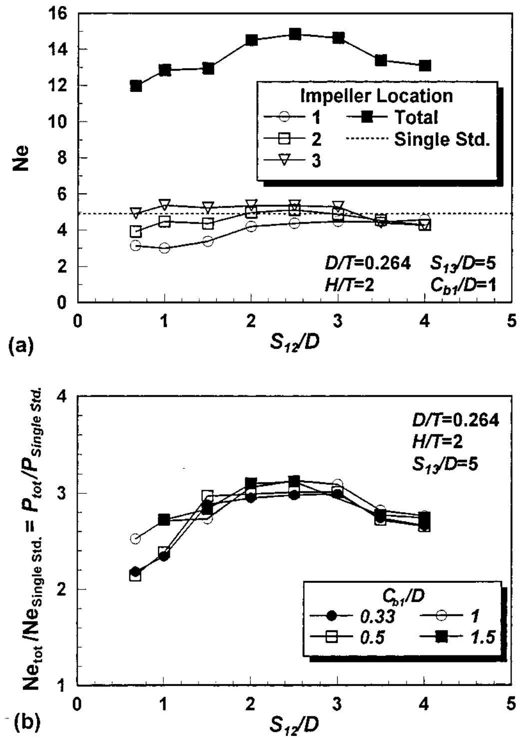

Figure 8. Triple-impeller system: (a) power numbers of individual impellers and total power number (equal to the sum of the power numbers of the individual impellers) as a function of S_{12}/D ratio; (b) effect of S_{12}/D ratio on the ratio of total power number (equal to the sum of the power numbers of the individual impellers) to the power number of a single impeller in the standard position ($C_{b1}/D = 1$, $Ne_{\text{Single Std.}} = 4.92$).

diminished with increasing C_{b1}/D and S_{12}/D values (Figure 7a–c). When the middle impeller was close to the highest impeller ($S_{12}/D = 4$; Figure 7c), the power drawn by any of the impellers was similar to one another and lower than that for $S_{12}/D = 2.5$. As a result, the power drawn by any of the impellers became similar to that of the lowest impeller and was nearly independent of C_{b1}/D.

Figure 8a shows the variation of the overall power number, Ne_{tot}, and the individual power numbers, Ne_i, as a function of S_{12}/D, for $C_{b1}/D = 1$. This figure shows that when two impellers were close to each other, independently of their location in the vessel, their individual power numbers decreased. This is also apparent from Figure 8b in which the effect of the spacing between the lowest and middle impeller on Ne_{tot} is reported. Full power was drawn when each impeller was far away from the others ($Ne_{tot}/Ne_{\text{Single Std.}} = 3.1$ for $S_{12}/D = S_{23}/D = 2.5$), as reported previously when total power measurements were made (Abrardi et al., 1990; Chiampo et al., 1991).

Finally, in Figure 9 the effect of impeller spacing on individual fractional power consumption is given. In general, $P_3 > P_2 > P_1$. This difference is very significant at very low clearances and small spacing between the lowest and middle impellers (Figure 9a,b). However, even for $C_{b1}/D = 1$ and moderate impeller spacing, appreciable differences in power consumption by individual impellers can be observed (Figure 9c). These results indicated that even in triple-impeller configurations the presence of a tickler impeller near the vessel bottom results in only minor increases in the overall power dissipation.

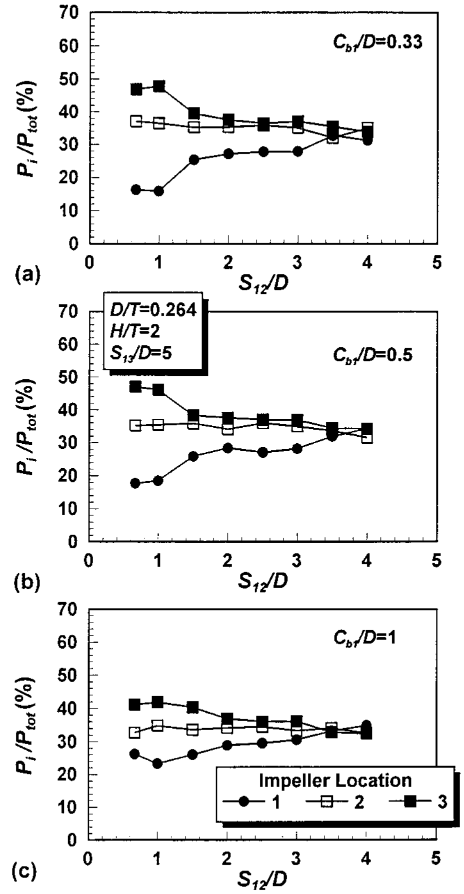

Figure 9. Triple-impeller system: Ratio of power consumed by individual impellers to total power consumption as a function of S_{12}/D: (a) $C_{b1}/D = 0.33$; (b) $C_{b1}/D = 0.5$; (c) $C_{b1}/D = 1$.

Conclusions

In single-impeller systems, the power drawn was found to be a decreasing exponential function of the off-bottom impeller clearance. In any multiple-impeller systems, the overall power dissipated was, in general, proportional to the off-bottom clearance of the lowest impeller and the impeller spacing. However, for S/D (or S_{12}/D) $\cong$ 1.5 and $C_{b1}/D >$ ~0.5, Ne_{tot} and P_{tot} decreased with C_{b1}. In both double- and triple-impeller systems, the lowest disk turbine was found to draw less power than the other turbines, i.e., (P_3>) $P_2 > P_1$. The total power consumption was approximately equal to the sum of each individual power consumption only when the spacing was about twice the impeller diameter and the C_{b1}/D ratio at or above 1.5. The results obtained in this work can be used to determine not only the overall power consumption of multiple-DT systems but also the power dissipated by individual disk turbines.

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Nomenclature

a = constant
B = baffle width (m)

C_{b1} = off-bottom clearance of the lowest impeller, measured from the bottom edge of the disk blade to the bottom of the vessel (m)
C_{b2} = off-bottom clearance of the upper impeller (in double-impeller systems) or the middle impeller (in triple-impeller systems), measured from the bottom edge of the disk blade to the bottom of the vessel (m)
C_{b3} = off-bottom clearance of the highest impeller (in triple-impeller systems), measured from the bottom edge of the disk blade to the bottom of the vessel (m)
C'_1 = off-bottom clearance of the lowest impeller, measured from the middle of the impeller to the bottom of the vessel (m)
D = impeller diameter (m)
H = height of liquid in the vessel (m)
$k_{\text{gauge } i}$ = proportionality factor for generic strain gauge i (with i = 1, 2, or 3), relating the torque imposed on the gauge to the electric signal produced by it (W·s/mV)
L_{G-I} = distance between an impeller and the strain gauge above it (m)
n = number of impellers
N = agitation speed (rotations/s, rps, or rotations/min, rpm, as indicated)
Ne = Newton number (power number)
Ne_i = Newton number (power number) of individual impeller i (with i = 1, 2, or 3), as defined in eq 2
Ne_{tot} = total (cumulative) Newton number (power number) of all impellers
$Ne_{\text{Single Std.}}$ = Newton number (power number) of a single impeller at standard conditions ($C_{b1}/D = 1$, $D/T = 0.352$, and $H/T = 1$)
P_i = power drawn by individual impeller i (with i = 1, 2, or 3) (W)
P_{tot} = total (cumulative) power drawn by all impellers (W)
$P_{\text{Single Std.}}$ = power drawn by a single impeller at standard conditions ($C_{b1}/D = 1$, $D/T = 0.352$, and $H/T = 1$) (W)
Re = impeller Reynolds number ($\rho ND^2/\mu$)
S = spacing (distance) between impellers in a double-impeller system (m)
S_{ij} = spacing (distance) between impeller i and impeller j (with i = 1, 2, or 3; j = 2 or 3) in a triple-impeller system (m)
T = vessel diameter (m)
w_b = vertical width of impeller blade (m)

Greek Symbols

τ = torque (N·m)
Φ_i = electrical signal produced by strain gauge i (with i = 1, 2, or 3) (mV)
ρ = liquid density (kg/m^3)
μ = liquid viscosity (kg/(m·s))
ω = angular velocity of the impeller (rad/s)

Acronyms

DT = six-blade disk turbine
FBT = six-blade flat-blade turbine
PBT = six-blade 45° pitched-blade turbine

Literature Cited

Abrardi, V.; Rovero, G.; Sicardi S.; Baldi, G.; Conti, R. Sparged Vessels Agitated by Multiple Turbines. *Proc. 6th Eur. Conf. Mixing* **1988**, 329−336.

Abrardi, V.; Rovero, G.; Baldi, G.; Sicardi S.; Conti, R. Hydrodynamics of a Gas−Liquid Reactor Stirred with a Multiple-Impeller System. *Trans. Inst. Chem. Eng., Part A* **1990**, *68*, 516−522.

Armenante, P. M. and Uehara Nagamine, E. Solid Suspension and Power Dissipation in Stirred Tanks Agitated by One or Two Impellers at Low Off-Bottom Impeller Clearances. *Proc. 9th Eur. Conf. Mixing* **1997**, 73−80.

Bates, R. L.; Fondy, P. L.; Corpstein, R. R. An Examination of Some Geometric Parameters of Impeller Power. *Ind. Eng. Chem. Process Des. Dev.* **1963**, *2*, 310−314.

Bates, R. L.; Fondy, P. L.; Fenic, J. C. Impeller Characteristics and Power. In *Mixing*; Uhl, V. W.; Gray, J. B., Eds.; Academic Press: New York, 1966; Vol. I, pp 111−178.

Bujalski, W.; Nienow, A. W.; Chatwin, S.; Cooke, M. The Dependency on Scale of Power Numbers of Rushton Disc Turbines. *Chem. Eng. Sci.* **1987**, *42*, 317−326.

Chiampo, F.; Guglielmetti, R.; Manna, L.; Conti, R. Gas−Liquid Mixing in a Multiple Impeller Stirred Vessel. *Proc. 7th Eur. Conf. Mixing* **1991**, *2*, 333−341.

Chudacek, M. W. Impeller Power Numbers and Impeller Flow Numbers in Profiled Bottom Tanks. *Ind. Eng. Chem. Process Des. Dev.* **1985**, *24*, 858−867.

Gray, D. J.; Treybal, R. E.; Barnett, S. M. Mixing of Single and Two Phase Systems: Power Consumption of Impellers. *AIChE J.* **1982**, *28*, 195−199.

Hudcova, V.; Machon, V.; Nienow, A. W. Gas−Liquid Dispersion with Dual Rushton Turbine Impellers. *Biotechnol. Bioeng.* **1989**, *34*, 617−628.

Kuboi, R.; Nienow, A. W. The Power Drawn by Dual Impeller Systems Under Gassed and Ungassed Conditions. *Proc. 4th Eur. Conf. Mixing* **1982**, 246−261; Paper G2.

Lu, W.-M.; Yao, C.-L. Gas Dispersion in a Multi-Stage Impeller Stirred Tank. *Proc. 7th Eur. Conf. Mixing* **1991**, *2*, 351−357.

Machon, V.; Vlcek, J.; Skrivanek, J. Dual Impeller Systems for Aeration of Liquids: An Experimental Study. *Proc. 5th Eur. Conf. Mixing* **1985**, 155−169.

Mahmoudi, S. M.; Yianneskis, M. The Variation of Flow Pattern and Mixing Time with Impeller Spacing in Stirred Vessels with Two Rushton Impellers. *Proc. 7th Eur. Conf. Mixing* **1991**, *1*, 17−24.

Nienow, A. W.; Lilly, M. D. Power Drawn by Multiple Impellers in Sparged Agitated Vessels. *Biotechnol. Bioeng.* **1979**, *21*, 2341−2345.

Nocentini, M.; Magelli, F.; Pasquali, G.; Fajner, D. A Fluid-Dynamic Study of a Gas−Liquid, Non-Standard Vessel Stirred by Multiple Impellers. *Chem. Eng. J.* **1988**, *37*, 53−59.

Raghava Rao, K. S. M. S.; Joshi, J. B. Liquid Phase Mixing in Mechanically Agitated Vessels. *Chem. Eng. Commun.* **1988**, *74*, 1−25.

Rewatkar, V. B.; Raghava Rao, K. S. M. S.; Joshi, J. B. Power Consumption in Mechanically Agitated Contactors Using Pitched Bladed Turbine Impeller. *Chem. Eng. Commun.* **1990**, *88*, 69−90.

Roustan, M. Power Consumed by Rushton Turbines in Non-Standard Vessels Under Gassed Conditions. *Proc. 5th Eur. Conf. Mixing* **1985**, 127−141; Paper 14.

Rushton, J. H.; Costich, E. W.; Everett, H. J. Power Characteristics of Mixing Impellers. *Chem. Eng. Prog.* **1950**, (Part I) *46*, 395−402; (Part II) *46*, 467−476.

Shiue, S. J. and Wong, C. W. Studies on Homogenization Efficiency of Various Agitators in Liquid Blending. *Can. J. Chem. Eng.* **1982**, *62*, 602−609.

Smith, J. M.; Warmoeskerken, M. M. C. G.; Zeef, E. Flow Conditions in Vessels Dispersing Gases in Liquids with Multiple Impellers. In *Biotechnology Processes: Scale-up and Mixing*; Ho, C. S., Oldshue, J. Y., Eds.; American Institute of Chemical Engineers: New York, 1987; pp 107−115.

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