Lehn M., Myers K.J., Bakker A. (1999) Agitator Design for Solids Suspension under Gassed Conditions, Canadian Journal of Chemical Engineering, Vol. 77, October 1999, page 1065-1071.

NOTE

Agitator Design for Solids Suspension under Gassed Conditions

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Design of mechanical agitators for solids suspension under gassed conditions can be achieved using a constant ungassed torque criterion if the solids suspension task is more difficult than the gas dispersion task. When gas dispersion is the more difficult task, design for complete gas dispersion will ensure solids suspension. Evidence supporting this approach is very strong for radial-flow impellers, but less so for up-pumping and down-pumping axial-flow impellers.

La conception d'agitateurs mécaniques pour la suspension de solides en conditions aérées peut être effectuée à l'aide d'un critère de couple non aéré constant lorsque la suspension des solides est plus difficile à réaliser que la dispersion du gaz. Lorsque la dispersion du gaz est plus difficile à réaliser, une conception basée sur la dispersion complète du gaz assurera la suspension des solides. Les preuves soutenant cette approche sont très évidentes pour les turbines à écoulement radial, mais moins pour les turbines à écoulement axial à pompage ascendant et à pompage descendant.

Keywords: gassed solids suspension, solids suspension, gas dispersion, three-phase agitation.

Agitator design for three-phase (gas–solid–liquid) operation is a challenging and industrially-relevant task. Chapman et al. (1983) investigated this problem in detail, relating the just-suspended speed to liquid and solid physical properties in a Zwietering-like (1958) manner. For radial-flow impellers they found that the increase in just-suspended speed under aerated conditions ($\Delta N_{js} = N_{jsg} - N_{jso}$) was linearly related to the volumetric gas flow rate. Such a simple relation was not found for up-pumping or down-pumping axial-flow impellers.

Frijlink et al. (1990) related the increase in just-suspended speed under aerated conditions to the cavity structure that forms on aerated impeller blades and the associated drop in impeller power draw. They correlated their gassed just-suspended speed data in the following manner:

$$\frac{N_{P_{js_g}}}{N_{P_{js_o}}} = \left(\frac{N_{js_g}}{N_{js_o}}\right)^{-n} \quad (1)$$

where the just-suspended power number was defined in terms of the liquid density:

$$N_{P_{js}} = \frac{P_{js}}{\rho_l N_{js}^3 D^5} \quad (2)$$

The exponent n of this correlation was found to be 1.1 for down-pumping axial-flow impellers, and 2 for radial-flow and up-pumping axial-flow impellers. Recently, Pantula and Ahmed (1997) found these same exponents and pointed out that an exponent of 2, as found for radial-flow and up-pumping axial-flow impellers, corresponds to a constant torque criterion; that is, the just-suspended torque under gassed conditions is equal to the just-suspended torque under ungassed conditions ($M_{jsg} = M_{jso}$, where torque is defined as $M = P/2\pi N$). There is no apparent physical meaning for an exponent of 1.1 as was found for down-pumping axial-flow impellers.

The present work examines the constant-torque design criterion including comparison of the difficulty of the solids suspension and gas dispersion tasks. In addition, solid property effects are studied, since they were not considered by Frijlink et al. (1990) and Ahmed and Pantula (1997).

Experimental apparatus and method

All experiments were performed in a 0.441 m diameter, flat-bottom vessel. The vessel was constructed of clear acrylic so the vessel contents, including the base, could be viewed. Four baffles were spaced at 90° around the vessel periphery. The baffle widths were equal to 1/12 of the vessel diameter (T/12), and the baffles were offset from the vessel wall by a distance equal to 1/6 of the baffle width (T/72). The baffles extended almost the entire height of the vessel, but stopped at a distance equal to 1/2 the baffle width (T/24) from the vessel base. All impellers had a diameter of 0.178 m (D/T = 0.404) and were placed at an off-bottom clearance equal to 25% of the vessel diameter (C/T = 0.25). Square batch geometry in the ungassed condition (Z_o/T = 1) was used in all instances.

Four axial-flow impellers were studied, including a pitched blade turbine (P-4), the Chemineer HE-3, and three and four-blade versions of the Prochem Maxflo impeller (MF-3 and MF-4). These axial-flow impellers were studied in both the up-pumping and down-pumping modes (designated by U and D, respectively). Three radial-flow impellers, the Chemineer S-4, D-6, and CD-6, were studied. All impellers were supplied by Chemineer, Inc. (Dayton, OH). Figure 1 shows the impellers while Table 1 describes them in more detail.

The liquid phase was always water, while the gas phase was air, which was introduced through a 0.178 m sparge ring placed near the vessel base (note that the sparge ring diameter was equal to the impeller diameter). Gas flow rates

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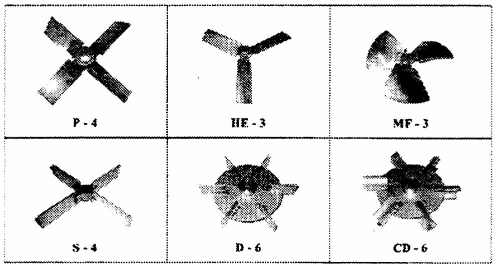

Figure 1 — Impellers studied (all axial-flow impellers are shown in the down-pumping mode, but were studied in both the up-pumping and down-pumping modes; the Maxflo (MF) impeller is shown in only a three-blade configuration, but was studied in both three and four-blade configurations).

TABLE 1
Impellers Studied (all axial-flow impellers were studied in both the up-pumping and down-pumping modes)

Impeller	Flow Pattern	Blades	Blade Angle	Hub Style	*W/D*
CD-6	Radial	6 semicircular	90 degrees	Disc	0.20
D-6	Radial	6 flat	90 degrees	Disc	0.20
S-4	Radial	4 flat	90 degrees	Open	0.17
HE-3	Axial	3 narrow profiled	Standard	Open	Standard
MF-3	Axial	3 wide profiled	Standard	Open	Standard
MF-4	Axial	4 wide profiled	Standard	Open	Standard
P-4	Axial	4 flat	45 degrees	Open	0.20

up to 0.00306 m^3/s were studied (corresponding to superficial gas velocities up to 0.0200 m/s or 2.72 vvm).

All impellers were studied in three-phase operation with an acrylic solid, which had a density of 1179 kg/m^3, a characteristic length of 3200 μm, an oval cylinder shape, and a terminal settling velocity of 0.0767 m/s in quiescent water. This solid can be characterized as moderately difficult to suspend. Selected impellers were also studied with an easily-suspended solid and a difficult-to-suspend solid. The easily-suspended solid was an ion exchange resin that had a density of 1053 kg/m^3, a characteristic length of 780 μm, a spherical shape, and a terminal settling velocity of 0.0132 m/s in quiescent water. The difficult-to-suspend solid was sand that had a density of 2670 kg/m^3, a characteristic length of 360 μm, a granular shape, and a terminal settling velocity of 0.0508 m/s in quiescent water. For a given impeller, the relative ungassed just-suspended speeds for these three solids were experimentally found to be 1, 1.6, and 3.6 (resin, acrylic, and sand, respectively). The solids loading (solids mass to slurry mass ratio) was always 10%.

Frijlink et al. (1990) used glass beads and sand in their work, both of which had diameters of 120 microns and densities of 2500 kg/m^3. Ahmed and Pantula (1997) used glass beads with a mean diameter of 174 μm and a density of 2500 kg/m^3. These solids are comparable to each other, indicating that the influence of solid properties has not been thoroughly examined in previous work. These solids are also comparable to the sand used in this work, although they are smaller. Both of these previous studies used water as the liquid phase and air as the gas phase.

Three types of experiments were performed. First, the just-suspended speed for solids suspension in two-phase (liquid–solid) operation was determined using Zwietering's (1958) two-second criterion. Although no gas was used in these experiments, the sparge ring was in the vessel. Then, the speed required to completely disperse the gas in two-phase (gas–liquid) operation was determined. For the radial-flow and up-pumping axial-flow impellers, complete dispersion was taken to occur when the gas was driven to and turned downward at the vessel wall (Chapman et al., 1983). For the down-pumping axial-flow impellers, complete dispersion was taken to occur when the impellers were indirectly loaded (Frijlink et al., 1990). The final experiments were the determination of the just-suspended speed in three-phase (gas–liquid–solid) operation.

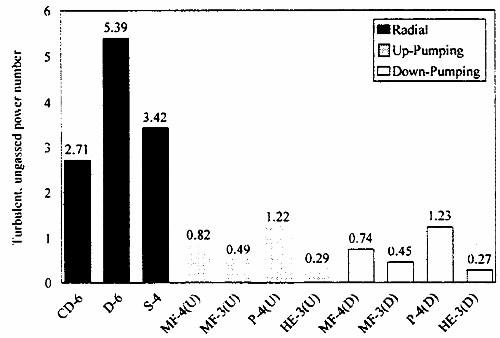

Figure 2 — Turbulent, ungassed power numbers of the impellers studied.

All just-suspended and complete-dispersion speeds were determined visually. The rotational speeds were measured with a zero velocity magnetic pickup and gas flows were measured with a calibrated rotameter. A calibrated strain gauge reaction torque sensor (Lebow model 2404-100) yielded torque measurements that were conditioned (Daytronics model 9171) to provide an accuracy of better than five percent.

Results and discussion

Figure 2 illustrates that the turbulent, ungassed power numbers of the impellers that were studied vary by a factor of twenty, with the radial-flow impellers having the highest power numbers and the profiled-blade axial-flow impellers having the lowest power numbers. The up-pumping and down-pumping power numbers of the axial-flow impellers were found to be similar, but not identical (Myers and Bakker, 1998).

Impeller performance comparisons will be based on torque requirements for a number of reasons. First, torque is the primary factor in determining the initial capital cost of an agitator, and it is typically used for design optimization. Second, although there are differences in torque and power comparisons, these differences are minor and do not change the primary conclusions of this work. The final reason for using torque comparisons is that the design criterion to be examined, as previous literature has suggested, is based on torque (Ahmed and Pantula, 1997; Frijlink et al., 1990).

The ungassed just-suspended torque requirements with the acrylic solid at a loading of 10 mass % are presented in Figure 3. The down-pumping axial-flow impellers can be seen to be superior to the up-pumping axial-flow and radial-flow impellers for this application. In addition, the down-pumping impellers with profiled blades (MF-3(D), MF-4(D), and HE-3 (D)) have substantially lower just-suspended torque requirements than the flat-blade P-4(D) impeller. In

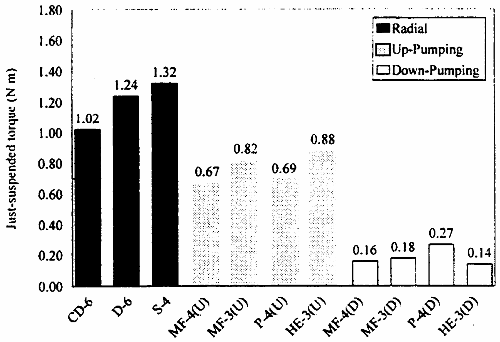

Figure 3 — Ungassed just-suspended torque requirements (obtained with the acrylic solid at a loading of ten mass percent).

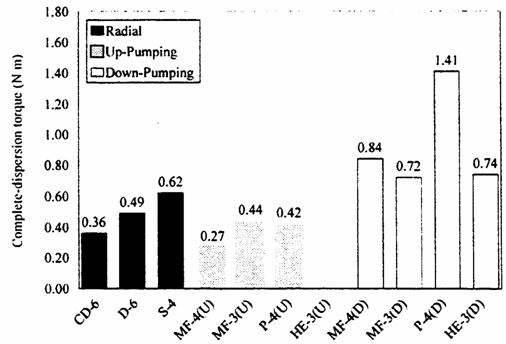

Figure 4 — Complete gas dispersion torque requirements (obtained at a superficial gas velocity of 0.0100 m/s with no solid present).

Table 2
Zwietering *S* Factors

Impeller	Zwietering *S* Factor
CD-6	10.4
D-6	8.46
S-4	10.9
MF-4(U)	15.3
MF-3(U)	21.9
P-4(U)	13.0
HE-3(U)	30.9
MF-4(D)	8.37
MF-3(D)	11.2
P-4(D)	8.34
HE-3(D)	12.6

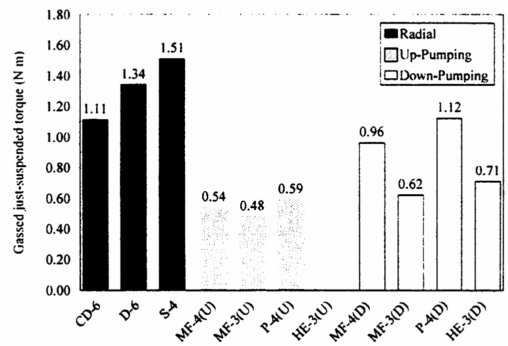

Figure 5 — Gassed just-suspended torque requirements (obtained with the acrylic solid at a loading of ten mass percent and a superficial gas velocity of 0.0100 m/s).

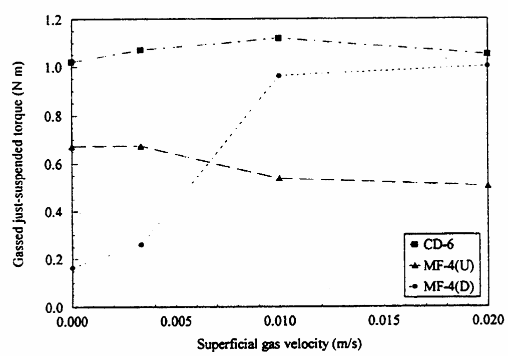

Figure 6 — Gassed just-suspended torque requirements of selected impellers (obtained with the acrylic solid at a loading of ten mass percent and at superficial gas velocities from zero to 0.0200 m/s).

the up-pumping mode, the four-blade impellers outperform the three-blade impellers in solids suspension applications. The just-suspended speed data taken with the acrylic solid is presented in terms of Zwietering *S* factors in Table 2. This factor is defined in the following manner:

$$S = \frac{N_{js} D^{0.85}}{\nu^{0.1} d_p^{0.2} \left(g \frac{\rho_s - \rho_l}{\rho_l} \right)^{0.45} B^{0.13}} \qquad (3)$$

The Zwietering *S* factor depends on geometric factors and would only apply at the conditions studied here (D/T = 0.404 and C/T = 0.25).

Figure 4 compares the torque requirements for complete gas dispersion at a superficial gas velocity of 0.0100 m/s (corresponding to 1.36 vvm). In this application, the down-pumping axial-flow impellers perform poorly. Also, the complete dispersion torque requirements of the down-pumping axial-flow impellers are susceptible to large fluctuations as the rising gas flow opposes the liquid pumping of the impeller (Hari-Prajitno et al., 1998). The complete dispersion torques of the up-pumping axial-flow and radial-flow impellers do not exhibit large fluctuations and are of similar magnitudes, with the up-pumping axial-flow impellers having lower torque requirements in general. The four-blade up-pumping axial-flow impellers (MF-4(U) and P-4(U)) out-perform the three-blade up-pumping axial-flow impellers (MF-3(U) and HE-3(U)) in gas dispersion. No data is presented for the up-pumping HE-3(U) impeller because it was not capable of dispersing the gas at rotational speeds as high as 15 s^{-1}.

The just-suspended torque requirements of all impellers for gassed solids suspension are compared in Figure 5. This data was taken with the acrylic solid at a loading of 10 mass % and a superficial gas velocity of 0.0100 m/s (1.36 vvm). A broader comparison of selected impellers at various gas flow rates is shown in Figure 6. These three impellers were chosen as the best of each impeller type (radial: CD-6; up-pumping axial: MF-4(U); and down-pumping axial: MF-4(D)).

Even though it did not exhibit the lowest torque and power requirements for gassed solids suspension, the four-blade version of the Maxflo impeller was chosen over the three-blade axial-flow impellers (MF-3 and HE-3) in both the up and down-pumping modes for this comparison. This choice was made because the four-blade Maxflo provided more stable operation and was far less susceptible to flooding and sudden, dramatic loss of solids suspension capability (Chapman et al., 1983).

The results of Figure 6 are similar to those reported by others (Chapman et al., 1983; Frijlink et al., 1990; Pantula and Ahmed, 1997), with the down-pumping axial-flow impeller exhibiting the lowest torque and power requirements at the lowest gas flow, and the up-pumping axial-flow impeller exhibiting the lowest torque and power requirements at higher gas flows. Under no circumstances did the radial-flow impeller exhibit the lowest torque or power requirement.

All gassed solids suspension data presented up to this point has been obtained with the acrylic solid that is moderately difficult-to-suspend. Experiments were also performed with an easily-suspended solid (ion exchange resin) and a difficult-to-suspend solid (sand). These experiments were performed only with the CD-6 and the up and down-pumping four-blade Maxflo (MF-4). The relative torque (gassed torque to ungassed torque ratio) required for gassed solids suspension is presented in Figure 7. For the radial-flow CD-6 impeller (Figure 7a), the relative torque for gassed solids suspension is essentially constant for the acrylic solid and sand, supporting the use of constant torque as a design criterion. However, the torque required to suspend the ion exchange resin increases with increasing gas flow. For the up-pumping four-blade Maxflo impeller (Figure 7b), the torque required for gassed solids suspension decreases somewhat with increasing gas flow, making the constant-torque design criterion conservative. For the down-pumping four-blade Maxflo impeller (Figure 7c), the torque required for gassed solids suspension increases with increasing gas flow, but the relative increase is different for the various solids.

In Figure 8 the absolute torque required for gassed solids suspension is compared with the torque required for ungassed solids suspension and the torque required for complete gas dispersion. With the radial-flow CD-6 impeller (Figure 8a), the torques required for gassed solids suspension of the acrylic solid and sand are relatively constant with gas flow rate and considerably greater than the torque required for complete gas dispersion. However, with the easily-suspended ion exchange resin, the torque required for complete gas dispersion at higher gas flows is greater than the torque required for ungassed solids suspension. Under these conditions, the torque required for gassed solids suspension follows the torque required for complete gas dispersion. Chapman et al. (1983) alluded to a similar effect observed during their study. For a radial-flow impeller (Rushton/D-6 style), they found that the gas was almost always dispersed before the solids were suspended (therefore, solids suspension was the more difficult task). The one exception was easily-suspended polystyrene for which solids suspension was achieved simultaneously with complete gas dispersion, implying that gas dispersion was the more difficult task in that instance. So, the data of the current study supports the constant-torque design criterion for radial-flow impellers as long as the solids suspension task is more difficult than the gas dispersion task. If gas dispersion is the

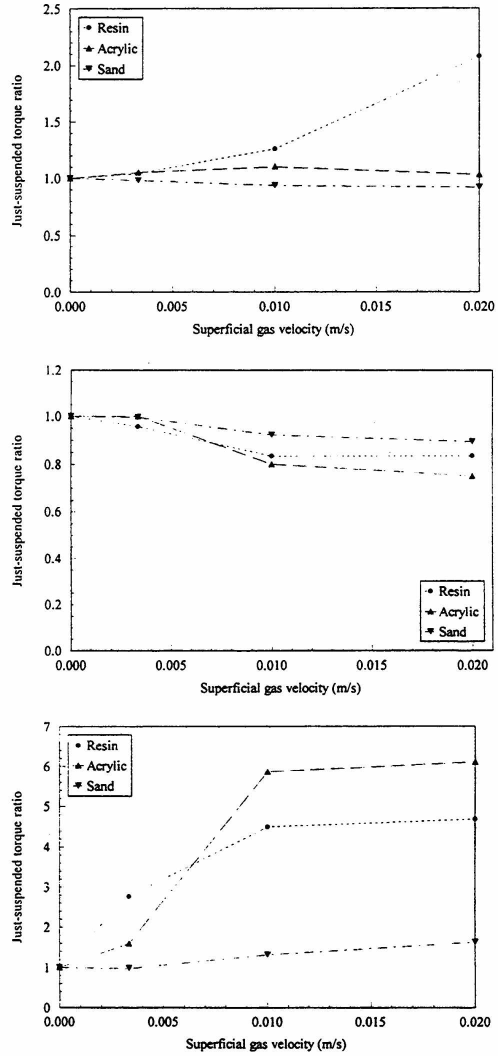

Figure 7 — Gassed to ungassed torque ratios for just-suspended conditions with various solids (a) CD-6 impeller; (b) MF-4(U) impeller; (c) MF-4(D) impeller (obtained at a solids loading of ten mass percent and at superficial gas velocities from zero to 0.0200 m/s).

more difficult task, design for complete gas dispersion will ensure solids suspension.

In Figure 8b, the torque required for ungassed solids suspension with the up-pumping four-blade Maxflo impeller can be seen to always be comparable to, or greater than, the torque required for complete gas dispersion. Also, the torque required for gassed solids suspension with the up-pumping Maxflo impeller decreases with increasing gas flow rate for all solids studied. This may be due to the gas flow reinforcing the flow pattern of the up-pumping impeller, but this is only a hypothesis. With the easily-suspended ion exchange resin, the gassed solids suspension torque does

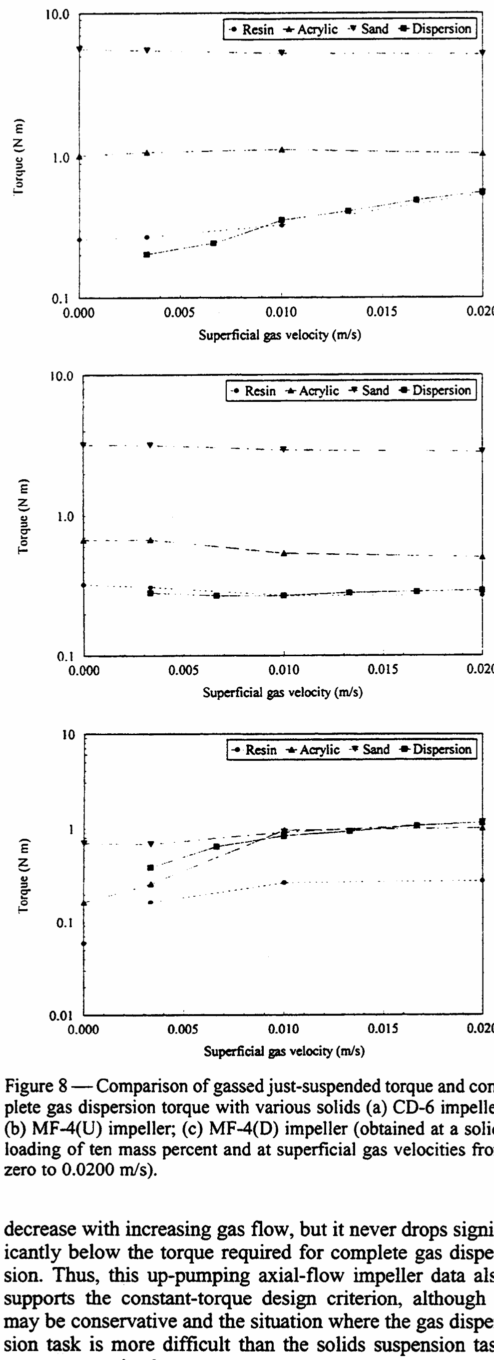

Figure 8 — Comparison of gassed just-suspended torque and complete gas dispersion torque with various solids (a) CD-6 impeller; (b) MF-4(U) impeller; (c) MF-4(D) impeller (obtained at a solids loading of ten mass percent and at superficial gas velocities from zero to 0.0200 m/s).

decrease with increasing gas flow, but it never drops significantly below the torque required for complete gas dispersion. Thus, this up-pumping axial-flow impeller data also supports the constant-torque design criterion, although it may be conservative and the situation where the gas dispersion task is more difficult than the solids suspension task was not examined.

The gassed solids suspension torque of the down-pumping Maxflo impeller is compared to the ungassed solids suspension and complete gas dispersion torques in Figure 8c. For the moderately difficult-to-suspend acrylic solid, the torque required for complete gas dispersion is always higher than the torque required for ungassed solids suspension, and the torque for gassed solids suspension approximately follows that required for complete gas dispersion (scatter in this data may be due to the difficulty in experimentally determining the point of gassed suspension and dispersion with a down-pumping impeller). For the difficult-to-suspend sand, the torque for ungassed solid suspension is higher than that for complete gas dispersion at the lowest gas flow rate. At this lowest gas flow rate, the torque for gassed solid suspension is equal to the torque for ungassed solid suspension, again supporting the constant-torque design criterion. At the higher gas flow rates, the torque for complete gas dispersion is greater than that for ungassed solids suspension of the sand, and the torque for gassed solids suspension is again approximately equal to that for complete gas dispersion. The easily-suspended ion exchange resin does not follow any clear trend, with the gassed solids suspension torque increasing with increasing gas flow rate, but always being less than that required for complete gas dispersion. Experimental observations indicate that since this solid is so easy to suspend, it can be suspended without the gas being dispersed. The liquid movement caused by the gas and impeller, although not directed towards the vessel base, is sufficient to suspend the solid.

Comparison of the data in Figures 3 through 5, taken with the acrylic solid, also supports the use of the torque-based design for the more difficult task. The gassed just-suspended torques (Figure 5) of the radial-flow CD-6, D-6, and S-4 impellers are very similar to the ungassed, just-suspended torques (Figure 3), both of which are significantly greater than the torque required for complete gas dispersion (Figure 4). The gassed just-suspended torques of the up-pumping axial-flow MF-3(U), MF-4(U), and P-4(U) impellers are similar to, but lower than, the ungassed just-suspended torques. Again, these just-suspended torques are higher than the torques required for complete gas dispersion. For the down-pumping axial-flow HE-3(D), MF-3(D), MF-4(D), and P-4(D) impellers, the gassed just-suspended torques are comparable to the complete gas dispersion torques and substantially greater than the torques required for ungassed solids suspension.

Figure 9 presents the dependence of the gassed to ungassed power number ratio (N_{pjsg}/N_{pjso}) on the gassed to ungassed just-suspended speed ratio (N_{jsg}/N_{jso}) for the data taken during this study. This is the correlation form proposed by Frijlink et al. (1990) and presented in Equation (1). For all of the radial flow impellers (Figure 9a) and with almost all of the solids considered, the exponent n is 2, agreeing with the findings of Frijlink et al. (1990) and Pantula and Ahmed (1997). However, two data points taken with the CD-6 impeller suspending the ion exchange resin do not agree with the correlation. These points do not follow the correlation because they were obtained when the gas dispersion task was more demanding than the solid suspension task (refer to Figure 8a). Since both Frijlink et al. (1990) and Pantula and Ahmed (1997) studied only relatively difficult to suspend solids, they did not encounter this situation.

A good portion of the data obtained with up-pumping axial-flow impellers is also described by the Frijlink et al. (1990) correlation with an exponent of 2 (Figure 9b), including all of the data taken with the difficult-to-suspend solid. However, with the other solids at higher gas flow rates, the gassed just-suspended speed can actually be less than the ungassed just-suspended speed. This is believed to occur because the gas reinforces the flow produced by the

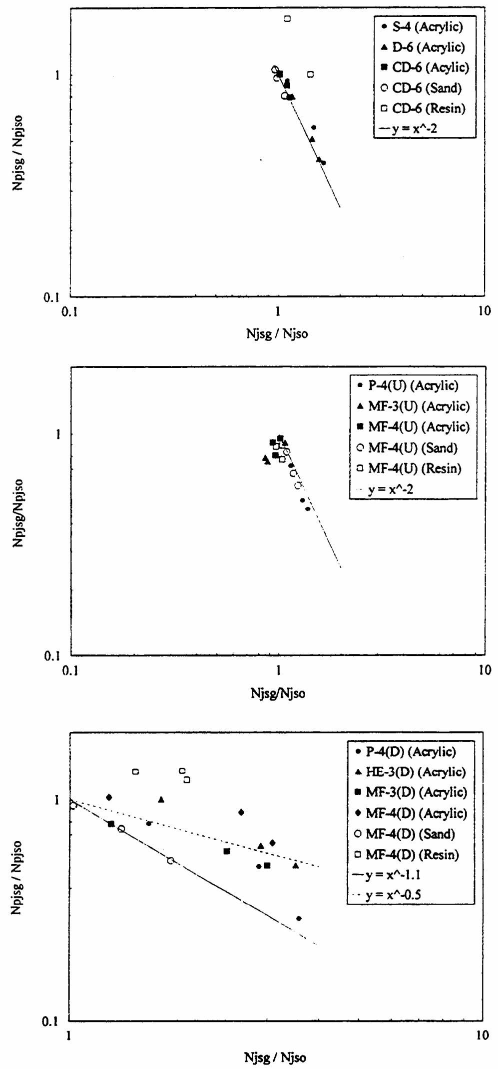

Figure 9 — Gassed to ungassed just-suspended power number ratio dependence on the gassed to ungassed just-suspended speed ratio (a) Radial-flow impellers; (b) Up-pumping impellers; (c) Down-pumping impellers.

impeller, thus reducing the just-suspended speed. Again, since they used only difficult-to-suspend solids, neither Frijlink et al. (1990) or Pantula and Ahmed (1997) studied conditions where this behaviour was observed.

The data taken with sand and a down-pumping axial-flow impeller is described by an exponent of 1.1 (Figure 9c), in agreement with Frijlink et al. (1990) and Pantula and Ahmed (1997). However, the data taken with the easier-to-suspend acrylic solid is not described by an exponent of 1.1; rather, an exponent of 0.5 describes this data, although there is considerable scatter. The data taken with a down-pumping axial-flow impeller and the easily-suspended ion exchange resin is also included in Figure 9c, and this data does not agree with the data taken with either of the other two solids. It is difficult to attach significance to the data obtained with the ion exchange resin because it could be suspended when the gas was far from dispersed. Since it is easy to suspend, the liquid motion caused by the gas flow and the directly loaded impeller was sufficient to suspend this solid.

Concluding remarks

This work has shown that the constant-torque approach ($M_{jsg} = M_{jso}$) is a valid design tool for gassed solids suspension if the ungassed solids suspension task is more difficult than the gas dispersion task. However, design for the gas dispersion task is appropriate if it is more difficult than the ungassed solids suspension task. This indicates that a general gassed solids suspension design procedure requires knowledge of each impeller's solids suspension performance, gas dispersion performance, and gassed power draw. The applicability of the combined constant-torque/more difficult task design criterion has been examined for radial-flow, up-pumping axial-flow, and down-pumping axial-flow impellers. Evidence of its applicability is very strong with radial-flow impellers. For up-pumping axial-flow impellers, the constant-torque approach is conservative at higher gas flows, and the gas dispersion task was always easier than the ungassed solids suspension task for the conditions studied here. For down-pumping axial-flow impellers, gas dispersion was more difficult than ungassed solids suspension for all but one data point, but the gassed solids suspension data did approximately follow the gas dispersion data. The down-pumping axial-flow impeller also exhibited the unusual behaviour that an easily-suspended solid could be suspended at conditions where the gas was not dispersed.

Nomenclature

B = solids mass to liquid mass ratio
C = impeller off-bottom clearance (measured from the lowest point on the impeller), (m)
D = impeller diameter, (m)
d_p = particle diameter, (m)
g = acceleration of gravity, (m/s^2)
M = torque, (N·m)
N = impeller rotational speed, (s^{-1})
N_p = $P/\rho N^3 D^5$, impeller power number
n = exponent of the correlation of Equation (1)
P = impeller power draw, (W)
S = Zwietering S factor defined in Equation (3)
T = vessel diameter, (m)
W = impeller blade width (actual, not projected), (m)
Z = liquid or slurry level, (m)

Greek letters

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

Subscripts, identifiers, and operators

D = down-pumping axial-flow impellers
g = gassed conditions
js = just-suspended conditions
l = liquid
o = ungassed conditions
s = solid
U = up-pumping axial-flow impellers
Δ = difference operator

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Manuscript received October 22, 1998; revised manuscript received April 14, 1999; accepted for publication April 16, 1999.