Solids Suspension with Axial-Flow Impellers

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Solids suspension in a vessel using mechanical agitation is a common unit operation in mineral, chemical, and other process industries. Solids suspension in vessels is used for hydrogenation, leaching, precipitation, slurry storage, and many other processes. Optimization of a specific solids suspension application includes design of an impeller/tank system that provides adequate off-bottom suspension, sufficient solids dispersion throughout the tank, and good liquid/solids mixing at a minimum power input. Predicting the dependence of impeller/tank geometry and solids/liquid physical properties on solids suspension is still an issue that receives considerable attention in the literature. Recent reviews were provided by Nienow (1992), Conti and Gianetto (1986), among other authors.

The pioneering work of Zwietering (1958) represents the most comprehensive investigation of the minimum suspension speed, despite the fact that many more correlations have been suggested since (Chapman et al., 1983; Armenante et al., 1998; Rao et al., 1988).

While there is a wealth of experimental data on the dependence of solids suspension on impeller diameter, impeller-to-tank bottom clearance, and fluid/solids physical properties, focus has not been on quantifying the impeller fluid dynamics and its influence on solids suspension.

It is known that at the just off-bottom suspension condition (N_{js}), the bulk fluid circulation velocity in a vessel is an order of magnitude higher than the particle-free settling velocity (Molerus and Lazel, 1987). This is also confirmed in our experimental investigation. Moleus and Lazel pointed out that this fact is a direct indication that solid particles inside the wall boundary layer determine the minimum bulk circulation velocity required for solids suspension. For fine particles (those smaller than boundary-layer thickness), a critical wall shear stress exists, above which particles are suspended.

The addition of a second impeller on the same shaft is known to modify the velocity field under the bottom impeller (Armenante and Chou, 1996). This suggests that impeller pumping will be modified by the addition of a second impeller. Armenante and Li (1993) showed that the presence of multiple impellers on the same shaft does not necessarily improve the off-bottom suspension.

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The objective of the present work is to investigate the pumping performance of axial-flow impellers and its influence on solids suspension. This will provide a basis for relating impeller pumping capacity to the S value in the Zwietering's correlation.

Experimental Setup and Procedures

The mixing tank consists of a $T = 390$-mm-dia. and 600-mm-high circular acrylic tank with a flat bottom placed inside a rectangular outer glass tank. This outer tank is filled with water to minimize the optical distortion. Four baffles 1/12 T in width and equally spaced were installed in the circular tank. Test impellers were mounted on a central shaft equipped with an Ono Sokki torque transducer and speed detector. The speed of this shaft could be varied from 0 to 1000 rpm by means of a variable-frequency drive. The speed and torque data were logged using a 486 PC equipped with a suitable data-acquisition board, and provided on-line analysis of power consumption, and so forth.

Pitch-bladed impellers of different pitch angles and all of the same diameter ($D = 0.160$ m) were used in the experiment (Table 1). Lightnin A310 impellers of the same diameter were also used in the investigation.

Velocity distributions were measured in the model mixing vessels using a TSI 2-dimensional (2-D) optical-fiber LDV system. The transmitting and receiving optics of this probe were mounted on an industrial robotic arm, allowing the probe to be automatically positioned within the tank. Because of the irregular sampling nature of the LDV method, bias correction had to be used to calculate time-mean statistics. The time-mean velocity data thus obtained were found repeatable to within 1%. Time-mean statistics of the velocity data were obtained using a time-weighted bias correction method incorporated in the TSI software package.

Spherical ballotini glass particles were used the solid phase (Table 2) and tap water was used as the liquid phase. Differ-

Table 1. Geometry of Pitch-Bladed Impellers

Impeller Pitch Angles (deg)	Blade Thickness (mm)	Blade Width	D/T	C/T
20, 25, 30, 35, 40, 45	1.5	1/5 D	0.41	1/3

Table 2. Solid Particles Properties

Particle Dia. (mm)	Particle Density (kg/m^3)	Conc. by Vol. ($C\nu$ %)
70	2520	22.5

ent particle sizes were used in the present work. However, only the data from the 70-μm particles were reported here. The subjective criteria suggested by Zwittering to determine N_{js} whereby particles remain on the bottom for periods of 1–2 s only is often used in the literature. In reality, a negligibly small number of particles usually remain on the tank bottom, while the main bulk of the solids is suspended. Typically the impeller speed will need to be doubled before these few particles are also suspended. In the present work, we used an approach similar to that used by Hicks et al. (1997); that is, the volume of settled particles was used as a measure of suspension. The just-off-bottom suspension speed, N_{js}, is defined at the condition when the settled particle-bed height becomes just visible, from observation through the tank walls, as the impeller speed is slowly reduced from a speed producing full suspension. The repeatability of the N_{js} measurement using this method was found to be within ± 1 rpm, or typically 1% of the impeller speed.

Results

Analysis: N_Q and N_{js}

It can be shown that suspension of solids is determined by the wall (or the tank bottom surface) shear stress (Molerus and Lazel, 1987). The critical-wall shear stress is a function of the circulation velocity, which can be characterized by the area-averaged impeller pumping velocity at the impeller exit:

$$V = \frac{4Q}{\pi D^2},$$

where Q is the pumping flow rate, and D is impeller diameter. At the just-off-bottom suspension condition, the pumping velocity is

$$V_{js} = \frac{4}{\pi} N_{js} D N_Q,$$

where V_{js} is the just suspension velocity, N_{js} is the commonly used just-suspension impeller speed, and $N_Q = Q/(ND^3)$ is the flow number.

It is proposed that V_{js} is independent of the impeller geometry. In other words, $N_{js} * N_Q$ is expected to be insensitive to the impeller type, for a given impeller diameter and a solid/liquid system.

This is useful in evaluating the S parameter in Zwietering's correlation:

$$N_{js} = S \frac{\nu^{0.1} d^{0.2} (g \Delta\rho/\rho_L)^{0.45} X^{0.13}}{D^{0.85}},$$

where S is a nondimensional coefficient which is known to be dependent on impeller type, D/T and C/T (Nienow, 1992). The present analysis suggests that $N_Q * S =$ const., for a given impeller D. This implies that the known S value of a given impeller can be used to predict S for a newly designed impeller, provided that the flow numbers of both impellers are known.

The definitions of the other variables in the Zwietering's equation are listed in the notation section.

Pumping velocity measurement

Pitch-blade impellers pumping downward were tested in the mixing vessel using water, at a shaft speed of 300 rpm. The geometrical dimensions of these impellers are listed in Table 1.

The time-mean axial velocity distributions at a distance 10% D below the impeller center line were measured using the LDV. Figure 1 shows the velocity distributions at different blade pitch angles. Generally speaking, the maximum velocity was observed at $r/D \approx 0.4$. The magnitude of velocity reduces significantly toward the impeller tip (at $r/R = 0.5$) due to the pressure drop near the impeller tip. The maximum-velocity gradient corresponds to where tip vortices are located. It can also be seen from the figure that the pumping velocity at the impeller exit increases steadily as the pitch angle is increased, as does the velocity near the wall.

Figure 2 shows the flow number, obtained from integrating the velocity distributions, and the power number (P_0) variation with the pitch angle. The flow number of a 45° pitch-bladed impeller was also measured by Jaworski et al. (1996); their result is included for comparison, and shows good agreement.

Solids suspension experiments

Ballotini glass particles were used in solids suspension studies. N_{js} data measured for the six pitch-bladed impellers are plotted in Figure 3, showing a decreasing trend as pitch angle is increased, as is expected. When N_{js} is multiplied by the factor of N_Q, the data become independent of the pitch angle. Similar behavior was also found for experiments with different particle sizes and solid concentrations.

A Lightnin high-efficiency axial flow impeller A310 was also used in the measurement to examine the effect of impeller

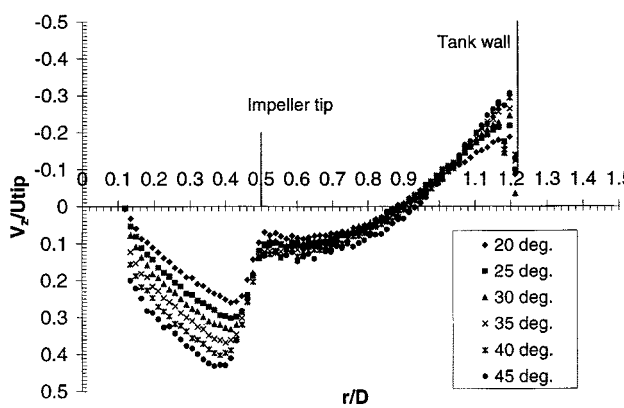

Figure 1. Pumping velocity distributions for the 6 pitch-bladed impellers.

Pitch blade angle $\alpha = 20, 25, 30, 35, 40, 45$ deg.

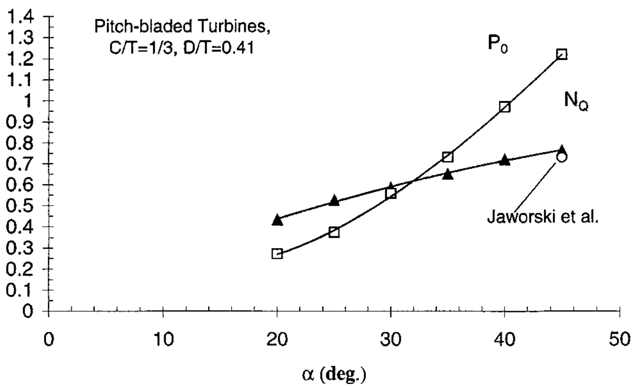

Figure 2. Variation of flow number and power number with pitch angle.

Impeller diameter $D = 0.160$ m, $T = 0.390$ m, $C = T/3$, $D/T = 0.41$. Test fluid: tap water. Shaft speed: $N = 300$ rpm.

type. Its data point of $N_{js} * N_Q$ is included in Figure 3, showing a close match to that of pitch-bladed impellers.

As an additional test case, a second A310 impeller was added one diameter above on the same shaft. The pumping-velocity profile underneath the bottom impeller was measured to obtain the flow number. The flow number was found to be 0.491, less than that of the single-impeller case (0.503). A solids suspension test was carried out as before. N_{js} was found to have increased from 230 rpm to 237 rpm, as listed in Table 3. Prediction of the just suspension speed of the dual impeller configuration was made by invoking $N_{js} * N_Q =$ const., and using the data from the single impeller N_{js}, that is, for the dual-impeller configuration:

$$N_{js} = \left(N_{js} * N_Q\right)_{\text{single impeller}} / \left(N_Q\right)_{\text{dual impeller}}.$$

The prediction of 236 rpm for the dual impeller configuration is in excellent agreement with the measured value of 237 rpm. It is worth noting that the flow number of the dual-impeller configuration ($\Delta C/D = 1$, $D/T = 0.41$) measured using LDV was found to be smaller than that of the single impeller. This results in an increase in the just suspension speed in the present dual-impeller configuration.

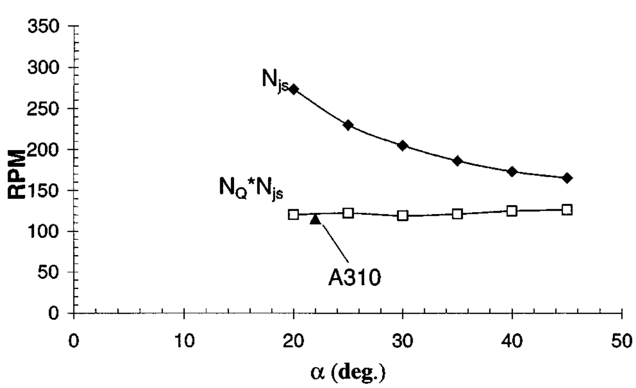

Figure 3. Variation of just-suspension speed with pitch angle.

Solid particle size $d_{50} = 70$ mm, $\rho = 2{,}520$ kg/m^3, fluid: water, $T = 0.39$ m, $H = 0.4$ m, $D/T = 0.41$, $CT = 1/3$ at solids loadings: $C\nu = 22.5\%$.

Table 3. Just-Suspension Speed of Single, Dual A310 Impellers

Impeller	N_{js} (rpm)	N_{js} Predicted	N_Q
Single A310	230	—	0.503
Dual A310	237	236	0.491

These data all confirm that the product $N_{js} * N_Q$ is independent of impeller type, for geometry at a given D/T and C/T, and for a given solid/liquid system. This is significant in that it provides a basis for relating impeller pumping capacity to the S value in the Zwietering correlation, that is, $N_Q * S =$ const. It should be emphasized that "$N_Q * s =$ const." is independent of the solid/liquid system. This also provides further evidence that the generic criterion for the just suspension is related to the wall shear stress, which is determined by the velocity outside the boundary layer.

Concluding Remarks

The pitch-bladed impellers at various pitch angles and the Lightnin A310 impellers of the same diameters used in the experimental investigation of impeller pumping and the just solids suspension speed. It is revealed that, for a given liquid/solid material system and a given impeller diameter, the product $N_{js} * N_Q$ is independent of the impeller geometry. This can be used to evaluate the S value in Zwietering's correlation. Addition of a second impeller on the same shaft deleteriously modifies the impeller pumping velocity. This results in a change in the just suspension speed, and the change can be predicted using the flow-number data. The present results suggest that the generic criterion for the just suspension is related to the wall shear stress, which is determined by the velocity outside the boundary layer.

Notation

C = impeller-to-tank-bottom clearance (m)
d = particle diameter (m)
N = impeller shaft speed (rpm)
r = radial axis (m)
ΔC = spacing between impellers (m)
U_{tip} = impeller tip velocity (m/s)
V_z = impeller axial velocity (m/s)
X = solids loading (weight of solids/liquid × 100)
α = pitch-blade setting angle, measured against the horizontal plane (deg)
ν = kinetic viscosity (m^2/s)
ρ_s = particle density (kg/m^3)
ρ_L = liquid density (kg/m^3)
$\Delta\rho = \rho_s - \rho_L$ (kg/m^3)

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