Suspension of High Concentration Slurry

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Introduction

Solid suspension in a vessel using mechanical agitation is a common unit operation in mineral, chemical, and other process industries. Solids suspension in vessels is often used for hydrogenation, leaching, digestion, precipitation, slurry storage, and many other processes.

In many cases, process throughput can be increased if a higher solid loading [such as $>20\%$ (v/v)] is used. It is of practical interest to understand tank off-bottom slurry suspension at high solid concentrations. While there is a wealth of information on suspension of solids in the low to median solid concentration range (Nienow, 1992), little information is available in the literature on agitation at high solid concentrations [such as 20–50% (v/v)]. Drewer et al. (1994) presented the power requirement for suspension of high concentration slurries. They found that with increasing concentrations, a point is reached where suspension is unattainable. The experimental range attained in their work was $C_v =$ 4–50% (v/v).

This article presents new data on agitation at high solid concentrations, showing different power features for axial flow and radial flow impellers. It will be shown that it is more energy efficient to use radial flow impellers at high solid concentrations.

Experimental Setup and Procedures

The mixing tank consists of a $T = 390$ mm diameter and 600 mm high circular acrylic tank with a flat bottom placed inside a rectangular outer glass tank. The 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 the shaft could be varied from 0 to 800 rpm by means of a variable frequency drive. The speed and torque were logged using a 486 PC equipped with a suitable data acquisition board, and provided online analysis of power consumption and so on.

Four different impellers, all with a diameter of 0.160 m, were used in the experimental investigation, as listed in Table 1. Two of these are pitch-bladed down-pumping axial flow impellers, and the other two are disc radial flow impellers. Flow numbers were obtained using laser Doppler velocimetry, as described by Wu et al. (1999). Figure 1 shows the mixing tank and impellers.

Table 1. Impeller Geometric Parameters*

Impeller	Flow	No. of Blades	Pitch Angle α	Blade Thick t/W	Flow No. N_Q	Power No. P_0
30PBT3	Axial	3	30°	4.7%	0.542	0.52
30PBT6	Axial	6	30°	4.7%	0.612	0.72
DT3	Radial	3	90°	4.7%	0.604	3.20
DT6	Radial	6	90°	4.7%	0.772	5.61

*Flow and power number data measured in water. Impeller diameters = 0.160 m.

Glass ballotini of $d_{50} = 105$ μm were used as the solid phase, and tap water was used as the liquid phase. The liquid/solids flow in the tank bottom was studied visually through the transparent tank walls, and through the transparent tank floor aided with a mirror. A method similar to that used by Hicks et al. (1997) using the volume of settled particles as a measure of suspension was employed. The just-off-bottom suspension speed, N_{js}, is defined as the point when the settled particle bed height just became visible, as the impeller speed is reduced from above the just-suspended speed. The repeatability of the N_{js} measurement using this method was found to be within ± 2 rpm, or typically 1% of the impeller speed.

Results

Maximum solids loading achievable

It is of practical interest to determine the maximum solid concentration at which slurry suspension can be maintained in a mechanically agitated vessel. Theoretically, the maximum solid concentration achievable in a mixing tank should be smaller than the sedimentation bed concentration C_{Vb} (this is usually referred to as the bed packing coefficient). It was found that $C_{Vb} = 0.58$ for the glass particles used in the present study, measured immediately after the solids were fully settled.

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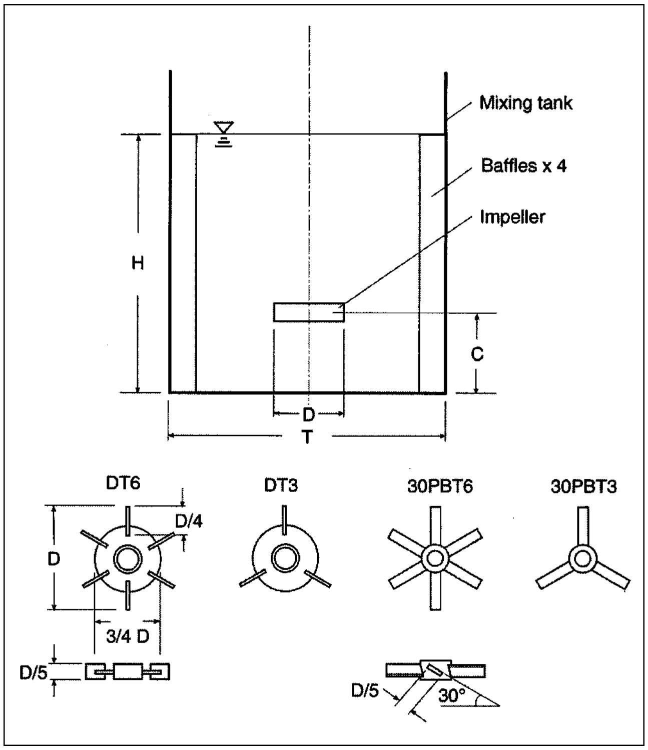

Figure 1. Mixing tank and impeller geometries.

Tank dia. $T = 0.390$ m; liquid height $H = 0.43$ m.

Figure 2 shows a typical example of the agitation power per unit slurry volume (P_{js}/V) required to just suspend solid particles from the tank bottom, as a function of reduced solid volume concentration normalized with the bed concentration. The impeller used was a down-pumping 30° pitch-bladed impeller, with six blades (30PBT6, refer to Figure 1 for geometry definition). Similar behavior was observed for other impeller types (such as radial flow impellers). It can be seen that the power required for just-off-bottom suspension increases rapidly with the concentration for $C_v/C_{Vb} > 0.9$ (corresponding to $C_v = 0.52$). It becomes practically impossible to go beyond this value. (In this region, even if the agitator was accidentally started, "bogging" of the agitator would happen eventually, leading to a shaft power which was so large that it threatened to burn out the motor and damage the torque meter.) This is similar to the finding reported by Drewer et al. (1994). In general, we may conclude that the maximum attainable solids loading in a mixing tank is

$$C_v/C_{Vb} = 0.90$$

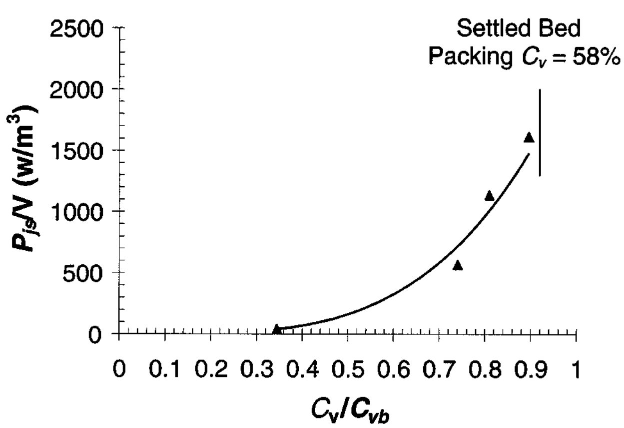

Figure 2. Variation of power required to suspend solids fully off tank bottom with relative solid concentration.

Tank dia. $T = 0.39$ m, impeller 30PBT6 pumping downward, impeller dia. $D = 0.16$ m, $C/T = 1/5$, $H/T = 1.08$. Solid particles: glass AE with $d_{50} = 105$ μm, $SG = 2.52$. Fluid: water.

Minimum impeller speed for off-bottom suspension

It should be pointed out that Zwietering's (1958) correlation, which is often used to calculate the minimum impeller speed required for complete off-bottom suspension, was not validated for high solids loading. This result is not surprising, as the suspension mechanisms at these high solid loadings are entirely different from those employed at low solid concentration, where the Zwietering correlation is normally used. Nevertheless, it is interesting to compare the values obtained for these two different regimes. For low solid concentration, the influence of solid loading on the just-off-bottom suspension speed N_{js} is empirically correlated as

$$N_{js} \propto X^a$$

where X is the arcane solid loading (weight of solids/weight of liquid$\times$100), and $a = 0.13$ for low solids loading (for example, $C_v < 20\%$).

The exponent a for high solid loading was found by measuring N_{js} over a solid loading range of $C_v = 40-52\%$, using four different impellers. The results are listed in Table 2. It can be seen from the table that a is higher than the value of 0.13 used by Zwietering (1958) for suspending high concentration solids. Radial turbines have a lower exponent than that of the axial flow impellers.

At the normal solid loading (for example $C_v < 20\%$), it is well documented in the literature that disc radial turbines (Rushton turbines) consume substantially more power than the down-pumping axial flow impellers in suspending solid particles (Ibrahim and Nienow, 1996; Frijilink et al., 1990), when there is no gas present. This characteristic was confirmed in our experiments with low solids loading (not shown here due to space limitation).

Figure 3 shows a comparison of the power required to just suspend solids off a tank bottom for the four different impellers, at a solid concentration of 49% (v/v). It can be seen that radial flow impellers require slightly less power than axial flow impellers to achieve off-bottom suspension. This is a rather surprising result as it is very different from the usual

Table 2. a-Exponent for Zwietering Correlation of High Solids Concentration

Exponent in $N_{js} \propto X^a$, for $C_v = 40-50\%$	Axial Flow Impeller (30PBT3, 30PBT6)	Radial Turbine DT3, DT6)
a	0.60–0.80	0.30–0.40

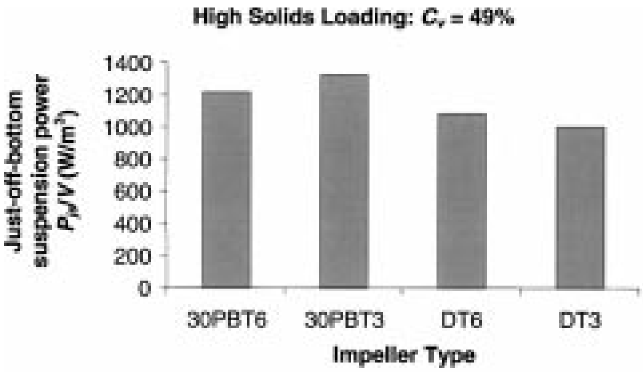

Figure 3. Power required to achieve just-off-bottom solids suspension at very high solids loading.

Impeller dia. $D = 0.16$ m, $C/T = 1/5$, $H/T = 1.08$, $T = 0.39$ m. Solid particles: glass AE with $d_{50} = 105$ μm, $SG = 2.52$. Fluid: water.

concept that axial flow impellers are far more energy efficient. This is a special feature which occurs at very high solids loading. The mechanism behind this is not clear and more work is needed to fully characterize this phenomenon.

Power number at high concentration

The power number is calculated from

$$P_0 = \frac{P}{\rho_{SL} N^3 D^5}$$

where ρ_{SL} is the slurry mixture density (kg/m^3) in the tank, N is the impeller speed (rev/s), and D is the impeller diameter (m). Power number variation with impeller speed ($> N_{js}$) at a solids concentration of 49% (v/v) is shown in Figures 4a and 4b for pitch-bladed turbines (30PBT3, 30PBT6) and Rushton turbines (DT3, DT6), respectively. Power number data measured with impellers operating in water are also shown (denoted by "water"). It can seen from Figure 4a that there is an increase in power number for pitch-bladed turbines when operating in high solids concentration, in comparison with operating in water. However, there is a reduction in power number for Rushton turbines when operating in high solids concentration (Figure 4b), when compared with that measured in water. This may be related to the fact that the damping at high solids loadings suppresses the dead flow zone at the back of the Rushton turbine blades, leading to a reduction of the drag. On the other hand, there is no dead flow zone behind the blades of pitch-bladed turbines (PBTs), and that increasing solids loading only leads to an increase in the skin friction, and, hence, an increase in drag coefficient. The above-mentioned features are rather surprising, and are not reported in the literature.

Conclusions

Experimental investigations have been carried out to characterize the main features of suspending high concentration solid particles in a model mixing tank. The study focused on suspending solid particles with a fast settling tendency. It was found that the maximum reduced solid concentration

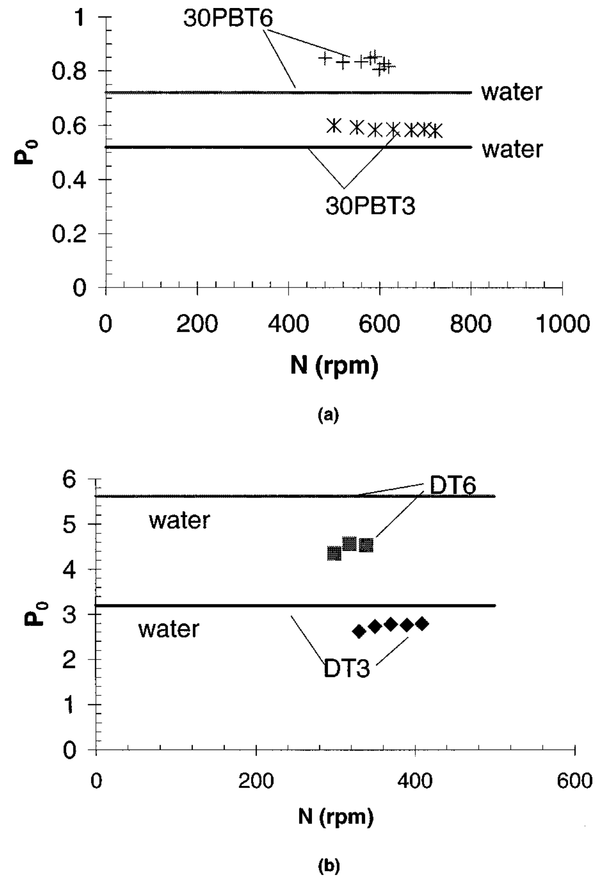

Figure 4. Power number variation with impeller speed, $P_0 = P/(\rho_{sl} N^3 D^5)$ where ρ_{SL} is the slurry density.

The lines denoted "water" are power numbers measured using water. Solids concentration $C_v = 49\%$, impeller diameter $D = 0.16$ m, $C/T = 1/5$, $H/T = 1.08$, $T = 0.39$ m: (a) pitch-bladed turbines; and (b) radial flow turbines.

(C_v/C_{Vb}) at which slurry suspension can be maintained is approximately 0.90. Higher than expected values of exponent a were found for the dependency of just-off-bottom impeller speed on solids loading in the high solids loading range. At high solids loading, radial impellers require relatively less power than axial flow impellers to suspend solids, opposite to what is observed in the low solids loading range. Therefore, it is more energy efficient to use radial flow impellers at high solid concentrations.

There is an increase in power number for pitch-bladed turbines when operating in high solids concentration, in comparison with operating in water. However, there is a reduction in power number for Rushton turbines when operating in high solids concentrations.

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Notation

a = the exponent used for solids loading effect on impeller speed
C_v = solid volumetric concentration, v/v

C_{Vb} = solid bed volumetric concentration, v/v
N = impeller shaft speed, rev·s^{-1} or rpm
N_{js} = just-suspension speed, rpm
N_Q = flow number
P = power, W
P_{js} = just-suspension power, W
P_0 = power number
t = impeller blade thickness, m
T = tank diameter, m
W = impeller blade width, m
X = solids loading, weight of solids/liquid $\times$ 100
α = pitch-blade setting angle, measured against the horizontal plane, degrees
ρ_{SL} = slurry density, kg/m^3

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