R&D NOTES

Suspension of Ultrahigh Concentration Solids in an Agitated Vessel

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Introduction

Particle suspension in stirred vessels has attracted considerable attention from researchers and engineers, as it is one of the important operating criteria in operations such as leaching, precipitation and adsorption in mineral processing and chemical industries. There have been many articles in the literature on solid–liquid agitated systems, but the majority are on systems with low-solids concentration (e.g., $<$ 0.20 v/v). On the other hand, many solid–liquid agitated systems, especially those in mineral processing operations, process slurry at high-solids concentration for the purpose of process intensification. Process intensification in agitated vessels often requires that the production rate per unit volume has to be increased without going through major changes in the plant. It is achieved by increasing the throughput or yield mostly through improved physical processes such as efficient mixing while retaining the existing vessel volume, since it is often impractical to reduce the size or volume of operating vessels.[1,2] In such instances, the concentration of solids in the agitated slurry will increase, leading to a significant increase in impeller power draw to achieve off-bottom solid suspension. The extra energy required at higher solid loadings is to compensate for the energy dissipation due to increased solid–liquid friction, particle–particle collisions, and particle-equipment collisions.[3] Raghava Rao et al[4] and Bubbico et al[3] agreed that the energy loss due to this mechanism is negligible at low-solids concentration ($<$ 0.04 v/v), but becomes appreciable at high-solids loading. To achieve complete off-bottom suspension at higher solids loading and minimize the energy dissipation at the same time, significant modifications in vessel/impeller geometry or vessel operating conditions are required. This study aims to determine the improved or modified tank and agitator designs and operating conditions required for handling the increased solids loading at optimum impeller power input. Furthermore, it aims to determine the maximum achievable solids concentration at which slurry suspension can be maintained under the modified conditions.

There have been many previous attempts to develop mathematical models and correlations to predict the influence of solids concentration on impeller speed and power required for off-bottom solids suspension. Narayanan et al[5] developed an expression for predicting the minimum velocity required

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to initiate the solids suspension based on the flow pattern, system geometry and physical properties of the two phases involved. Kee and Tan[6] proposed a CFD approach to predict the minimum impeller speed for just-off-bottom suspension (N_{js}) by observing the transient profiles of the solid-phase volume fraction at the base of the vessel. Kasat et al[7] also developed a CFD model using a two-fluid model with standard k-ε turbulence model with mixture properties for predicting solids concentration distribution. Nevertheless, these studies focused on suspensions with low-concentration slurries and the applicability of these approaches to high-concentration slurries has not yet been verified.

Wu et al[8] reported that, in a baffled agitated vessel, the maximum "achievable" concentration of spherical particles $(C_v)_{max}$ is 90% of the solids packing condition C_b, which is 0.58 v/v for a baffled tank. They reported that $(C_v)_{max} = 0.52$ v/v in a baffled tank and the energy efficiency of radial flow impellers at very high-solids concentration ($C_v = 0.49$ v/v) is greater than that of axial flow impellers in achieving just-off-bottom solids suspension. Recently, it was suggested by Wu et al[2,9] that the impeller power draw required for suspending high-concentration slurry can be reduced significantly if the mixing vessels are operated without baffles. However, they did not compare the maximum "achievable" solids loading in baffled vessels to that in unbaffled vessels. The effect of baffles cannot be ignored in the optimization of solid–liquid agitated vessels. The main role of baffles in mechanically agitated vessels is to prevent swirling and vortexing of liquid.[10] It is generally agreed that the presence of baffles enhances mixing and, consequently, increases mass- and heat-transfer rates. However, excessive or insufficient baffling may result in the reduction of bulk-liquid flow and localized circulation in the vessel.[10] Due to these reasons; it is likely that the maximum "achievable" solids loading in a baffled tank could be significantly different from that in an unbaffled tank. It is also possible that the specific impeller power input required to achieve the just-off-bottom suspended conditions at the maximum solids loading in a baffled tank could be different from that in an unbaffled tank.

Most of the previous studies on solid–liquid mixing found in the literature focus on solids suspension in low-viscosity liquids such as water. However, solids suspension in full-scale operations often occurs in viscous liquids. In many cases, the liquid phase in industrial operations could have a significantly high viscosity due to the large quantities of chemical and organic substances present. It is, therefore, useful to quantify the effect of liquid-phase viscosity on off-bottom suspension of high-concentration slurry. Although the information on the mixing of highly viscous fluids is relatively abundant,[11–15] very few researchers have studied the suspension of solids in viscous liquids. Ibrahim and Nienow[16] studied the effect of liquid viscosity on mixing patterns and solids suspension in agitated vessels. They stated that the predictions of critical impeller speed required to achieve just-off-bottom suspension (N_{js}) using Zwietering's equation[17] were not valid at high-liquid viscosity. They mentioned that predicted N_{js} results had up to 90% error when compared to their experimental results and, therefore, suggested that the phenomenon of solids suspension in viscous liquids is far more complicated than commonly accepted. Ibrahim and Nienow's work involved low-solids concentration ($C_w = 0.005$ w/w), and its conclusions are yet to be verified for solids suspension in viscous liquids for a range of solids concentration. Therefore, it will be valuable to investigate the influence of a small increase in liquid viscosity on N_{js} and specific impeller power input at N_{js}, especially for high-concentration slurries.

This article presents new information on specific impeller power draw required for solids suspensions at extremely high-solids concentration (up to 0.55 v/v), termed as ultra-high solids concentration. This study was carried out to investigate the effects of impeller type and baffling arrangement on impeller power consumption. To simulate the presence of impurities in the liquid phase and its influence on liquid viscosity, which is common in full-scale operations, liquids with viscosities higher than that of water were used in this study. The increase in liquid viscosity used in this study was small so as to maintain the turbulent regime in liquid flow which is essential for achieving off-bottom solids suspension. The results presented in this article will provide useful design data for optimizing the energy efficiency of mixing vessels handling high-concentration slurries.

Experimental

All experiments were carried out in a 0.39 m diameter (T) cylindrical, flat-bottom perspex tank placed inside a square outer glass tank. The cylindrical tank was equipped with four equally spaced baffles with width (B) to tank diameter ratio (B/T) of 1/12. The space between the inner and outer tanks was filled with tap water to minimize the optical distortion during flow visualization. Off-bottom impeller clearance was set at T/3. Impellers were mounted on a centrally driven shaft attached to an Ono Sokki torque transducer and speed detector. The impeller shaft was driven by an electric motor having a maximum speed of 550 rpm. The impeller speed was varied using a variable frequency drive.

Tap water was used as the primary liquid phase. Glycerol (BP 99.7% pure Nat Oleo supplied by APS Healthcare, Victoria, Australia) was added to water at various concentrations, to vary the liquid phase viscosity. A Bohlin CVO-50-controlled stress rheometer was used to determine the viscosity of Newtonian glycerol-water solutions before and after the experiment. The liquid height in the tank (H) was maintained equal to the tank diameter in all experiments. Spherical glass ballotini particles with a density of 2,500 kg/m^3 and a mean size (d_{50}) of 90 μm were used as the solid particles. Impellers used in this work are shown in Figure 1 and they were disc turbines, pitch-bladed turbines and a hydrofoil. All the impellers had a diameter of 0.16 m. Other dimensions and the power numbers of the impellers are shown in Table 1.

Zwietering[17] introduced the visual observation method to determine the critical impeller speed for just-off-bottom suspension N_{js}, which he defined as the impeller speed at which no solid particles are observed to remain at the tank bottom for more than 1 or 2 s. This criterion has been frequently used to measure N_{js} by many researchers.[18–19] However, Kasat and Pandit[20] pointed out that excessive energy is required to lift relatively small amounts of solids from stagnant regions around the periphery of the vessel bottom,

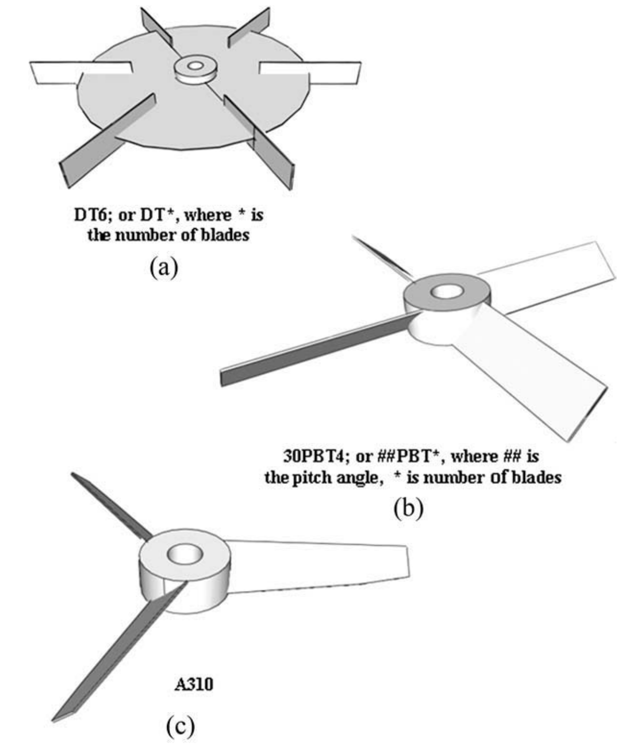

Figure 1. Impellers used in this study.

(a) radial flow impeller: DT6, (b) mixed flow impeller: 30PBT4, and (c) axial flow impeller: A310.

especially near the baffles or at the center of the vessel bottom, due to weaker liquid circulation at these locations. They also mentioned that, from a practical point of view, the amount of solids in these regions is generally insignificant, but could lead to up to 20–50% increase in impeller speed required for off-bottom solids suspension.

In this work, therefore, a method recommended by Wu et al[2,8–9] was used to determine N_{js}. In this method, the bed height of the settled solids at the tank bottom was used as a means of determining N_{js}. To determine N_{js} according to this method, the impeller speed was initially increased to a sufficiently high value so that no particles remained stationary at the tank bottom. At this condition, all particles were fully suspended from the tank bottom (Figure 2b). The impeller speed was then decreased gradually until a thin solids bed appeared at the tank bottom (Figure 2c). The impeller speed was then increased gradually and the speed at which the solids bed disappeared was designated as N_{js} (Figure 2b). The impeller speed had to be varied slightly up and down a few times around N_{js} before a repeatable reading for N_{js} was obtained. At N_{js} the height of settled solids bed $H_B \sim 0$. If the impeller speed was decreased below N_{js}, a visible solids bed appeared at the tank bottom whose height $H_B > 0$ (Figures 2c and 2d). Figure 2a shows that the slurry cloud height H_s is nearly the same as the liquid height at $N >> N_{js}$. It must be pointed out that at N_{js}, particles are not necessarily evenly distributed throughout the tank as shown in Figure 2a. In this study, H_B was measured between two baffles. The repeatability of N_{js} values determined using the aforementioned method was found to be typically within $\pm$ 2 rpm. The ratio of settled bed height (H_B), and total liquid height (H), is plotted against the impeller speed in Figure 3 for a tank operated with the 30PBT6 impeller. It can be seen that the normalized solids-bed height (H_B/H) is zero at N_{js}, and increases with a decrease in impeller speed. This method of using settled solids-bed height for determining N_{js} has been demonstrated by Wu et al[2,8,9,21] to be quite reliable for suspensions with high-solids concentrations.

Results

Maximum solids loading $(C_v)_{max}$ under baffled and unbaffled conditions

A typical plot of impeller power input at N_{js} per unit slurry volume (P_{js}/V) as a function of solids concentration C_v is shown in Figure 4 for 30PBT6. The specific power input (P_{js}/V) increases with increase in solids concentration under both baffled and unbaffled conditions. Under baffled condition, (P_{js}/V) increases gradually with an increase in solids concentration up to 0.3 v/v and, thereafter, it increases rapidly as the concentration approaches the maximum achievable value of $(C_v)_{\max} = 0.52$ v/v for this tank. Based on Figure 4, it may be concluded that the ratio of maximum solids loading to solids-packing coefficient in a baffled mixing tank is expressed as

$$(C_v)_{\max}/C_b \approx 0.90.$$

where the value of packing coefficient (C_b) is 0.58 v/v for the particles used in the current tests. The extremely high (P_{js}/V) required at high $(C_v)_{\max}$ can be attributed to various reasons including the high-energy loss due to particle-liquid friction, particle–particle collisions and particle-equipment collisions as suggested by Bubbico et al.[3] Under unbaffled conditions (Figure 4), the maximum achievable solids concentration $(C_v)_{\max}$ is 0.56 v/v which is higher than that at baffled condition. Based on Figure 4, for an unbaffled tank, it is estimated that

$$(C_v)_{\max}/C_b \approx 0.98.$$

As shown in Figure 4, for all C_v values, (P_{js}/V) values under unbaffled condition are lower than those under baffled

Table 1. Impeller Geometric Parameters (W: Blade Width; T: Tank Diameter; D: Impeller Diameter)

Impeller ID	Full Name	Flow Pattern	No. of Blades	Blade with W/D	D/T	Power No. N_p#
DT6	6-bladed radial turbine	Radial	6	1/5	0.41	5.598
DT4	4-bladed radial turbine	Radial	4	1/5	0.41	4.140
30PBT6	30° pitched 6-bladed turbine	Mixed	6	1/5	0.41	0.720
30PBT4	30° pitched 4-bladed turbine	Mixed	4	1/5	0.41	0.560
A310	Hydrofoil axial flow impeller	Axial	3	–	0.41	0.320

#Power number data measured in water

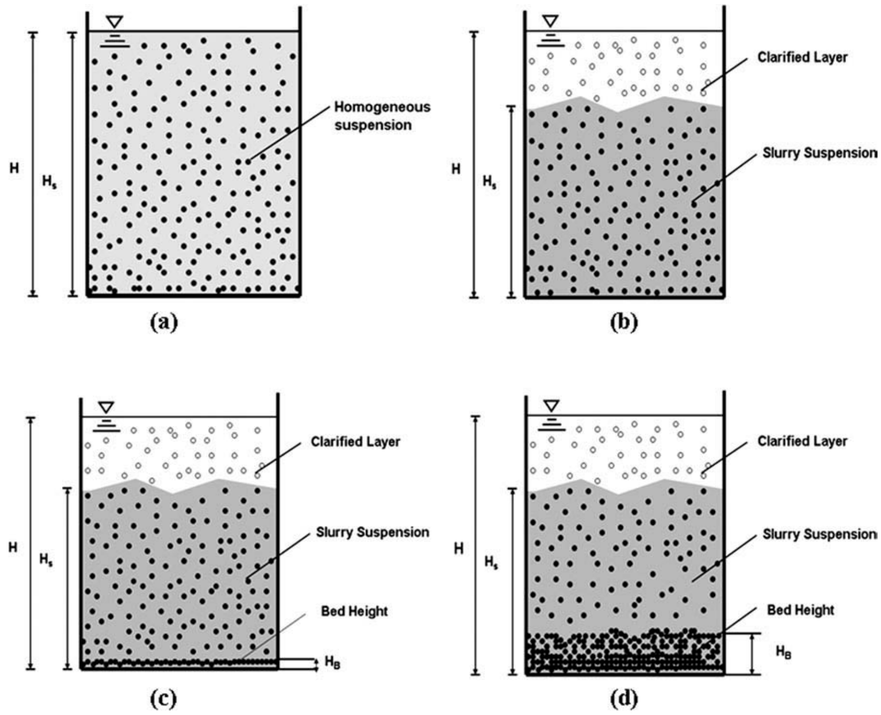

Figure 2. Visual method to determine the N_{js} (a) $N \gg N_{js}$, homogeneous suspension, $H_B = H$, (b) $N = N_{js}$, $H_B = 0$, (c) $(N_{js} - N) \approx 2$ rpm, $H_B > 0$, and (d) $N \ll N_{js}$, $H_B \gg 0$.

condition. These results show clearly that the removal of baffles is highly beneficial in decreasing the specific impeller power input, especially when very high-solids concentrations are suspended in agitated vessels.

Effect of impeller type on (P_{js}/V) at ultrahigh solids concentration

This study has also shown that at a relatively low-solids concentration $C_v = 0.15$ v/v, 30PBT6 (mixed flow impeller) and A310 (axial flow impeller) have lower (P_{js}/V) values at N_{js} than DT6 (radial flow impeller) for off-bottom solids suspension under baffled conditions (Figure 5a). However, under unbaffled condition, the (P_{js}/V) results exhibit an opposite trend for the same solids concentration (Figure 5b). DT6 is more energy efficient than 30PBT6 and A310 under this condition. Results shown in Figure 5b reinforce the point that the impeller with a higher power number (DT6) requires lower specific power input to suspend the particles at N_{js} under unbaffled condition as mentioned in our recent publication.[21]

(P_{js}/V) values for the same three impellers but at a higher solids concentration of 0.50 v/v are shown in Figure 5c for baffled condition. It is interesting to note that, in this case, DT6 has a lower specific power input at N_{js} as compared to 30PBT6. Wu et al[8] reported similar specific impeller power input results for these two impellers at a similar solids concentration (0.49 v/v). This result could be attributed to the

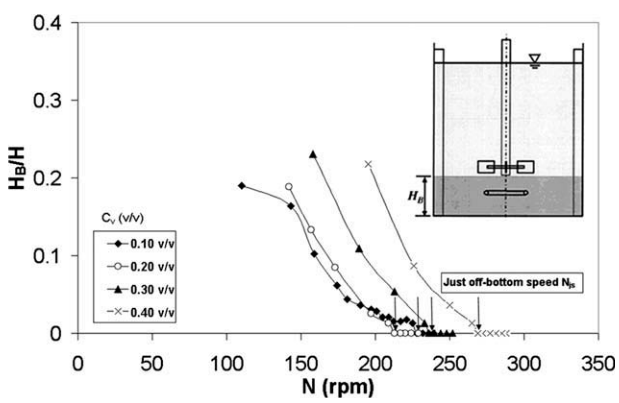

Figure 3. Sedimentation bed height (H_B) vs. impeller speed (N); N_{js} determination at different solids concentrations. Impeller: 30PBT6.

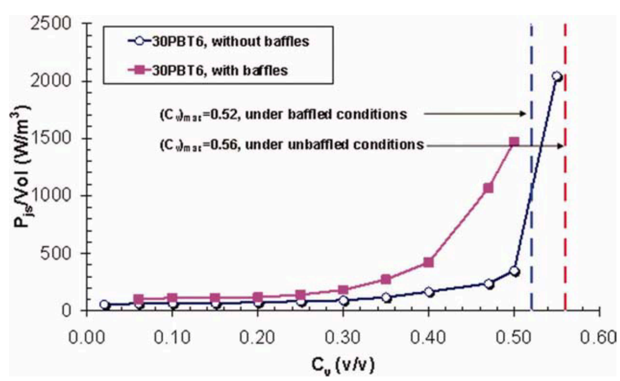

Figure 4. Specific impeller power input (P_{js}/V) at N_{js} as a function of solid concentration C_v. Impeller: 30PBT6 pumping downward.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

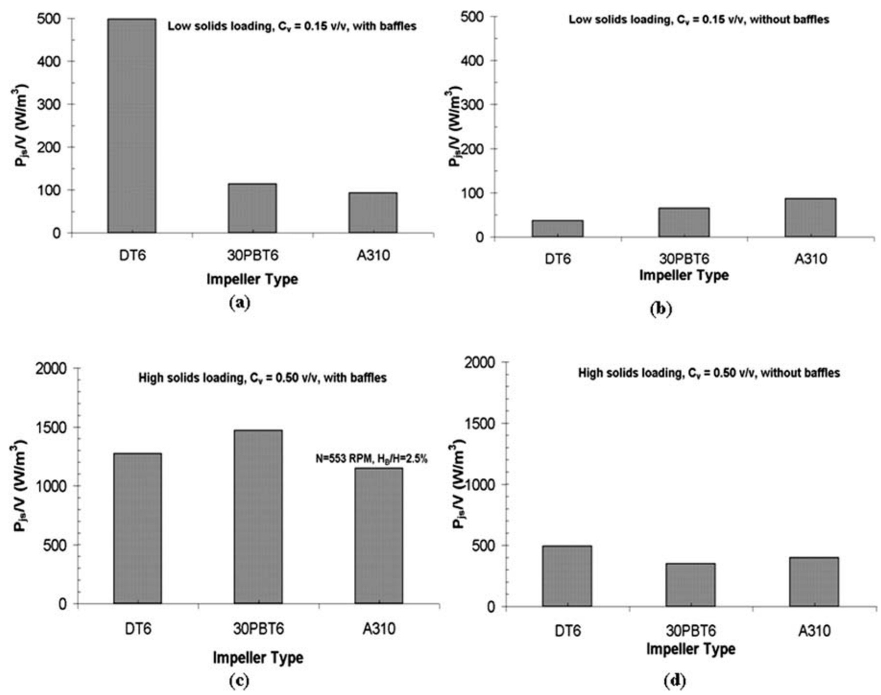

Figure 5. Specific power input (P_{js}/V) at N_{js} at different conditions (a) $C_v = 0.15$ v/v, baffled condition, (b) $C_v = 0.15$ v/v, unbaffled condition, and (c) $C_v = 0.50$ v/v, baffled condition, P_{js}/V data not available for A310, and (d) $C_v = 0.50$ v/v, unbaffled condition.

secondary flow circulation loop generated in the vessel by DT6 above the impeller plane. This flow loop possibly picks up the particles brought to the impeller plane by the flow loop below the impeller and suspends them in the upper parts of the vessel leading to higher slurry cloud height. The larger slurry cloud height for DT6 also indicates better utilization of the agitator for solids suspension and improved energy efficiency (i.e., low P_{js}).[22] It should be pointed out that at $C_v = 0.50$ v/v, the just-off-bottom suspension could not be achieved using A310 in this work because N_{js} for this impeller exceeded the maximum motor speed ($\sim$ 550 rpm).

(P_{js}/V) values for the three impellers at $C_v = 0.50$ v/v under unbaffled condition are shown in Figure 5d. In this case, 30PBT6 leads to the lowest (P_{js}/V) followed by A310 and DT6. This observation is rather interesting considering that DT6 is more energy efficient (has lower (P_{js}/V) values) compared to A310 and 30PBT at $C_v = 0.15$ v/v as shown in Figure 5b. The reason behind this phenomenon is not clear and further work is required to explain this.

Optimum solids loading (C_v)$_{osc}$

The specific impeller power input has been expressed as (P_{js}/V) so far, but it can be also expressed based on the total mass of solids suspended ε_{js} as shown in Eq. 1

$$\varepsilon_{js} = \frac{P_{js}}{M_s} \qquad (1)$$

where M_s is the mass (kg) of the solids in the tank. Drewer et al[19] justified this expression for ε_{js} based on the consideration that the rate of mass transfer or reaction is independent of agitation and vessel volume once the suspension of solids is achieved in the majority of processes, except for operations such as crystallization which requires suspension homogeneity. They suggested that for such processes, the reaction rate is controlled by the solids-surface area and, therefore, it is logical to evaluate the effect of solids concentration on specific impeller power based on the mass of solids suspended. Based on Drewer et al's suggestion, ε_{js} was calculated according to Eq. 1 and used in the evaluation of impeller power efficiency.

The ε_{js} values for 30PBT6 and DT6 impellers at various solids concentrations are shown in Figure 6 for water (μ = 0.001 Pa.s), and glycerol solution (μ = 0.023 Pa.s). When ε_{js} is plotted in this form, it can be seen that it decreases with an increase in C_v, reaches a minimum and then starts increasing. This trend is observed for both impellers in both liquids. The C_v value at which ε_{js} is a minimum is designated as "optimum solids concentration (C_v)$_{osc}$", because it represents a condition at which the energy input into the system through impeller rotation is used efficiently. The optimum solids concentrations for 30PBT6 and DT6 in water are found to be 0.25 and 0.35 v/v, respectively. In other words, at this concentration, more solids are suspended per unit of impeller power input (kg solids/W) compared to those at other C_v values. To illustrate this point, $1/\varepsilon_{js}$ (kg solids/W) data are shown in Figure 6 for selected C_v values. In all the cases, $1/\varepsilon_{js}$ (kg solids/W) values at optimum solids concentrations are greater than those at lower C_v values. For example, impeller 30PBT6 operating in water at the optimum C_v of 0.25 v/v can suspend about 4.5 kg solids per Watt of power, whereas at a lower C_v of 0.05 v/v, it can suspend only 1.92 kg solids per Watt of power. These results indicate that the energy efficiency of solid–liquid mixing vessels can be increased by operating them at higher solids concentration (ca. optimum C_v values) than hitherto thought.

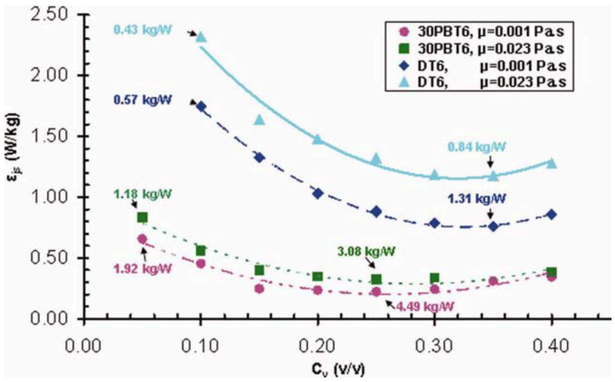

Figure 6. Specific impeller power input ϵ_{js} (= P_{js}/M_s) at N_{js} at different C_v, under baffled conditions. Liquid: water (μ = 0.001 Pa.s), and glycerol solution (μ = 0.023 Pa.s).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 6 also shows that ε_{js} values for DT6 are greater than those for 30PBT6 for all C_v values in both liquids. It is clear that an increase in liquid viscosity leads to an increase in ε_{js} values regardless of the impeller type and C_v used. However, the effect of viscosity in increasing ε_{js} is relatively more significant for DT6 than for 30PBT6. The optimum solids concentration $(C_v)_{osc}$, 0.25 v/v for 30PBT6 and 0.35 v/v for DT6, is not influenced by the increase in liquid viscosity. However, the ε_{js} values at these C_V values increase with increase in viscosity. These results indicate that the energy efficiency of these impellers will be lower if they are operated in liquids with higher viscosity, mainly because fewer particles will be suspended per unit of impeller power input under such conditions, regardless of the solids concentration of the slurry.

Unbaffled conditions for efficient solids suspension

The ε_{js} results for four different impellers (DT6, DT4, 30PBT6 and 30PBT4) at C_v = 0.40 v/v in liquids with different viscosities are shown in Figures 7a and 7b for baffled and unbaffled conditions, respectively. Under baffled condition, ε_{js} values for DT6 in all the liquids are lower than those for DT4 indicating that the higher power number DT6 is more energy efficient at high-solids concentration. On the other hand, there is no significant difference in ε_{js} values for 30PBT6 and 30PBT4 under baffled conditions in all the liquids. Under unbaffled condition, the ε_{js} values for the disc turbines (DT6 and DT4) in all the liquids are nearly the same. Similarly, ε_{js} values for the pitched blade impellers (30PBT6 and 30PBT4) are also nearly the same under unbaffled conditions. However, under unbaffled conditions, DT6 and DT4 impellers become less energy efficient (greater increase in ε_{js} values), with an increase in liquid viscosity when compared to 30PBT6 and 30PBT4 impellers (Figure 7b). Comparison of ε_{js} results for these four impellers suggest that DT6 or DT4 is more energy efficient when it is used in water under unbaffled conditions for $C_v = 0.40$ v/v.

The percentage reduction in ε_{js} due to the removal of baffles for the different types of impellers used in this study are shown in Table 2 for water (μ = 0.001 Pa.s), and glycerol solutions (μ = 0.015 and 0.023 Pa.s). At $C_v = 0.40$ v/v, removal of baffles leads to significant decrease in ε_{js} regardless of the impeller type and liquid viscosity. The reduction in ε_{js} varies from 56–80% in water to 36–61% in glycerol solution with μ = 0.023 Pa.s. It is also evident that the percentage reductions in ε_{js} for disc turbines are much higher than those for the pitched blade turbine impeller in all solutions. These results imply that it is possible to intensify the solid–liquid mixing process and still achieve significant reduction in impeller power input, even at relatively higher liquid viscosity and C_v, simply by removing baffles.

The effect of viscosity on ε_{js} at high-solids concentration (C_v = 0.40 v/v) and relatively high-liquid viscosity (μ = 0.023 Pa.s) has not been reported so far to the authors' knowledge. Attempts to determine ε_{js} at $\mu > 0.023$ Pa.s and $C_v > 0.4$ v/v were not successful in this study due to the limitations of the electric motor used.

Discussion

It is interesting to note that $(C_v)_{max}$ in solid–liquid mixing vessels can be increased by removing the baffles (Figure 4). This is most likely due to the strong swirling flow present at the tank bottom under unbaffled condition which promotes the suspension of solids. Removal of baffles also leads to a decrease in impeller power input even at high C_v which can

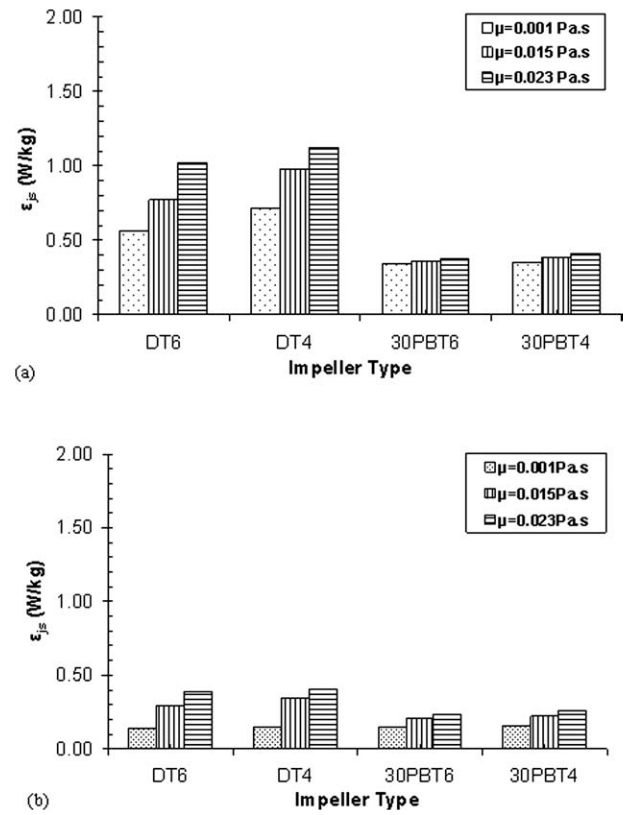

Figure 7. Specific impeller power input ε_{js} (= P_{js}/M_s) for different types of impellers in liquids with different viscosities for C_v = 0.40 v/v, (a) under baffled condition, and (b) under unbaffled condition.

Table 2. Percentage Reduction (%) in Impeller Power Consumption (ε_{js}) Due to the Removal of Baffles, $C_v = 0.40$ v/v

μ (Pa.s)	DT6 (N_p=5.598)	DT4 (N_p=4.140)	30PBT6 (N_p=0.720)	30PBT4 (N_p=0.560)
0.001	75	80	57	56
0.015	62	65	42	42
0.023	61	64	37	36

be attributed to the reduction in energy dissipation against the vessel walls. For example, nearly 80% reduction in specific impeller power input can be achieved for 30PBT6 by removing the baffles at $C_v = 0.50$ v/v (Figure 5).

Attempts made in this work to increase the solids concentration beyond $(C_v)_{max}$ were not successful because the considerably higher impeller power draw at these conditions was beyond the practical limit of the electric motor. It must be pointed out that the solids concentration of 0.55 (v/v) used in this study is extremely high, and there is no data for such high concentration in the literature to the authors' knowledge. Operating the mixing vessels at such high-solids concentration can easily lead to motor damage due to a sharp rise in impeller power consumption owing to the solids-packing effect. Drewer et al[23] also suggested that, at high-solids concentration, the effective viscosity of suspension changes suddenly giving rise to a significant change in suspension behavior and leading to complex flow circulations. Burn-out of electric motors is a possible consequence if mixing vessels in some mineral processes are operated at C_v greater than 0.40 v/v. On the other hand, using a dilute or relatively low-solids concentration condition is not beneficial to industry because it will increase the operating costs unnecessarily due to insufficient utilization of the existing infrastructure. In such instances, it will be highly beneficial to operate the mixing vessels at solids concentrations around the optimum values, which lie between the traditionally used low concentrations and impractical ultrahigh concentrations.

Two strategies have been suggested in this work to reduce the specific impeller power input, (1) operating the solid–liquid mixing vessel around optimum C_v, and (2) removal of baffles. The optimum C_v values shown in Figure 6 show that operating the agitated vessel at solids loadings higher than 0.25 v/v is feasible and beneficial in terms of impeller energy efficiency. Removal of baffles has been also shown to be an effective method to reduce impeller power consumption (up to 80%) at high-solids loadings (Figure 5). However, it is to be pointed out that slurry distribution and, therefore, its uniformity could be potentially affected without the baffles. Wu et al's suggestion that the dispersion of particles and liquid phase mixing time in solid–liquid mixing vessels are dependent on particle size, impeller type and baffling condition has to be taken into account before considering the removal of baffles.[21]

In the minerals processing industry, it is still common to find many agitated slurry tanks operating with low-solids loadings ($\ll 0.2$ v/v). Application of results reported in this study will enable such operations to intensify their processes while optimizing the impeller power consumption using relatively simple modifications such as removal of baffles and changing the impeller type.

Ibrahim and Nienow[16] conducted experiments in highly viscous Newtonian liquids but using relatively lower solids concentration (0.5% w/w). They suggested that the impeller power required achieving off-bottom solids suspension in highly viscous liquids is higher than that in water, which is consistent with the results reported in this article. The main difficulty associated with the suspension of solids in a viscous environment is obtaining a uniform mixture because there are fewer or no turbulent eddies in the system. The observations made in this work indicate that the impeller power required to achieve the off-bottom solids suspension in viscous liquids may be higher than that in water, but this still may not lead to uniform suspension.

Conclusions

Experiments have been carried out to investigate the impeller power required to achieve off-bottom suspension involving extremely high solids concentrations (up to 0.55 v/v) in an agitated vessel under baffled and unbaffled conditions. Results obtained in this work indicate that the ratio of maximum achievable solids concentration at N_{js} to solids bed-packing coefficient $(C_v)_{max}/C_b$ is around 0.98 under unbaffled conditions, which is higher than the 0.90 under baffled conditions.

The study on the effect of impeller type on specific impeller input at N_{js} $(= P_{js}/V)$ at a solids concentration higher than normal value ($C_v = 0.50$ v/v) showed that the disc turbine requires lower specific power than the pitched bladed impeller under baffled conditions. Nevertheless, under unbaffled conditions, the disc turbine requires higher specific power than the pitched blade and hydrofoil impellers to achieve off-bottom solids suspension. This observation is different from the usual ones reported in the literature which show higher power number impellers such as disc turbines are more efficient under unbaffled conditions, but at $C_v < 0.40$ v/v.

An increase in liquid viscosity led to an increase in specific impeller power consumption, regardless of the impeller type and solids concentration used. However, the optimum solids concentration at which ε_{js} $(= P_{js}/M_s)$ is minimum was not affected by liquid viscosity, but was influenced by the impeller type.

Removal of baffles was found to be beneficial for achieving process intensification, even in the viscous environment. Up to 80% reduction in impeller power consumption could be achieved by the removal of baffles even at solids concentrations higher than those used in industry.

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Notation

C_w = solids weight concentration, w/w
C_v = solids volume concentration, v/v
C_b = bed packing coefficient, v/v
$(C_v)_{osc}$ = optimum solids concentration, v/v

$(C_v)_{max}$ = maximum attainable solids concentration, upper limit, v/v
d = particle size, mm
D = impeller diameter, m
H = liquid level, m
H_B = settled bed height, m
H_s = slurry cloud height, m
M_s = mass of solids, kg
N = impeller speed, rev/min, rpm
N_p = power number
N_{js} = just-off-bottom solids suspension speed, rpm
P = power, W
P_{js} = agitator power for just-off-bottom solids suspension, W
T = tank diameter, m
V = tank volume (m^3), or velocity (m/s)
ε_{js} = agitator power per unit solids mass at the just-off-bottom solids suspension condition, W/kg
μ = viscosity, Pa.s
W = blade width, m

Literature Cited

1. Wu J,Graham L,Mehidi NN. Intensification of mixing. *J Chem Eng Jpn*. 2007;40:890–895.
2. Wu J,Nguyen B,Graham L. Mixing Intensification for the Mineral Industry. *Can J Chem Eng*. 2010b;88:447–454.
3. Bubbico R,Di Cave S,Mazzarotta B. Agitation power for solid-liquid suspensions containing large particles. *Can J Chem Eng*. 1998;76: 428–432.
4. Raghavo Rao KSMS,Rewatkar VB,Joshi JB. Critical impeller speed for solid suspension in mechanically agitated contactors. *AIChE*. 1998;34:1332–1340.
5. Narayanan S,Bhatia VK,Guha DK,Rao MN. Suspension of solids by mechanical agitation. *Chem Eng Sci*. 1968;24:223–230.
6. Kee NCS,Tan RBH. CFD Simulation of solids suspension in mixing vessels. *Can J Chem Eng*. 2002;80:1–6.
7. Kasat, GR,Khopkar AR,Ranade VV,Pandit AB. CFD simulation of liquid-phase mixing in solid-liquid stirred reactor. *Chem Eng Sci*. 2008;63:3877–3885.
8. Wu J,Zhu YG,Pullum L. Suspension of high concentration slurry. *AIChE*. 2002;48:1349–1352.
9. Wu J,Nguyen B,Graham L. Energy Efficient High Solids Loading Agitation for the Mineral Industry. *Can J Chem Eng*. 2010a;88:287–294.
10. Lu WM,Wu HZ,Ju MY. Effect of baffle design on the liquid mixing in an aerated stirred tank with standard rushton turbine impellers. *Chem Eng Sci*. 1997;52:3843–3851.
11. Todd DB. *Mixing of Highly Viscous Fluids, Polymers, and Pastes*. In: *Handbook of Industrial Mixing*. Hoboken, NJ: Wiley-Interscience; 2004;987–1024.
12. Niedzielska A,Kuncewicz CZ. Heat transfer and power consumption for ribbon impellers. mixing efficiency. *Chem Eng Sci*. 2005;60:2439–2448.
13. Fradette L,Thome G,Tanguy PA,Takenaka K. Power and mixing time study involving a maxblend impeller with vicious newtonian and non-Newtonian fluids. *Chem Eng Res Des*. 2007;85:1514–1523.
14. Cabaret F,Fradette L,Tanguy PA. Effect of shaft eccentricity on the laminar mixing performance of a radial impeller. *Can J Chem Eng*. 2008a;86:971–977.
15. Cabaret F,Fradette L,Tanguy P.A. New turbine impellers for viscous mixing. *Chem Eng Technol*. 2008b; 31:1806–1815.
16. Ibrahim S,Nienow AW. Comparing impeller performance for solid-suspension in the transitional flow regime with newtonian fluids. *Trans IChemE*. 1999;77:721–727.
17. Zwietering TN. Suspending of solid particles in liquid by agitators. *Chem Eng Sci*. 1958;8:244–253.
18. Bujalski W,Takenaka K,Paolilni S,Jahoda M,Paglianti A,Takahashi A,Nienow AW,Etchells, AW. Suspensions and liquid homogenisation in high solids concentration stirred chemical reactors. *Trans. IchemE*. 1999;77:241–247.
19. Drewer GR,Ahmed N,Jameson GJ. *An Optimum Concentration for the Suspension of Solids in Stirred Vessels*. In: *Mixing and Crystallization*. Netherlands: Kluwer Academic Publishers; 2000.
20. Kasat GR,Pandit A. Review on mixing characteristics in solid-liquid and solid-liquid-gas reactor vessel. *Can J Chem Eng*. 2005;83:618–643.
21. Wu J,Wang S,Graham L,Parthasarathy R,Nguyen B. High solids concentration agitation for minerals process intensification. *AIChE J*. 2010c. doi:10.1002/aic.12468.
22. Hicks MT,Myers KJ,Bakker A. Cloud height in solids suspension agitation. *Chem Eng Comm*. 1997;160:137–155.
23. Drewer GR,Ahmed N,Jameson GJ. Suspension of high concentration solids in mechanically stirred vessels. *IChemE Symp Ser*. 1994;136: 41–48.

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