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High Solids Concentration Agitation for Minerals Process Intensification

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By using mixing intensification involving high solids concentration as a means to achieve process intensification for the mineral process industry is discussed here. Improving agitator energy efficiency is essential for operating at high solids concentrations. It is shown that improved agitator energy efficiency can be achieved by removing baffles and using higher power number impellers at high solids loadings. Power consumption (50–80%) reductions were demonstrated in the experiments. It is also suggested that slurry stratification in tanks can be used to boost either solids residence time or slurry mass flow. Basic equations related to solids residence time and solids throughput are presented for guidance toward minerals process intensification. An example on doubling throughput via intensification is presented.
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Introduction

The modern minerals industry uses hydrometallurgical processes to extract metals from ores. Typically, a large volume of ore particles-in-chemical solution slurry is treated in large-scale mixing tanks in a mineral processing plant, for leaching, digestion, precipitation, and other chemical processing to obtain pure metals or concentrated ores. The slurry tanks used for minerals processing are typically large in dimensions: tanks of 20–30 m in height and 10–15 m in diameter are not uncommon. Often a large number of these slurry tanks are installed in parallel or in series for continuous chemical reactions (Figure 1). This makes it possible to deliver multimillion tons per year of refined metal or concentrated ore products continuously, even though the reactions may be slow, and require ore particles to be suspended in solutions over many hours or even days.

Because of the high capital cost to build a large mineral refinery, it is desirable to increase the throughput for a given

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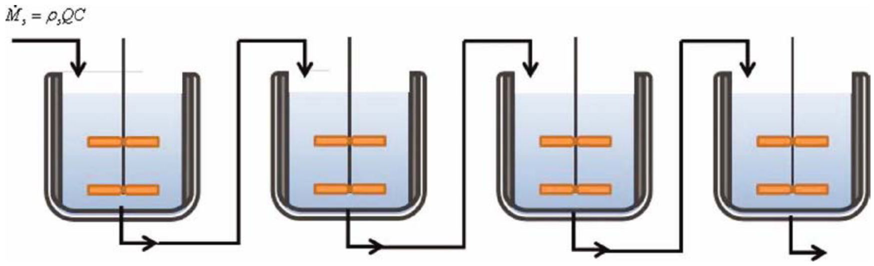

Figure 1. Slurry tanks used in the mineral industry: multiple slurry tanks in series for continuous processing.

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

tank installation volume, to achieve improved economic return on the capital investment. Process intensification in mixing tanks is considered an attractive approach toward this goal,[1,2] because ore slurries are mostly held in mixing tanks in such refineries. Process intensification could be defined as a means to drastically increase production yield per unit volume and per unit time and per unit cost. Wu et al.[2] suggests that the term mixing intensification be used to describe efforts to achieve process intensification in mixing tanks.

It may be obvious that one of the methods for mixing intensification is to operate the slurry processing tanks at high solids concentrations as suggested by Refs. 1 and 2. A key issue following this approach is elevated agitation power consumption; particularly, as the solids concentration approaches the solids packing coefficient, the power tends to increase exponentially.[3,4] Thus, it is critical to develop agitator/tank designs to minimize the power consumption at high solids concentrations.

It has been generally accepted that axial flow or mixed flow impellers are more energy efficient than radial flow impellers for off-bottom solids suspension in tanks, installed with vertical baffles. The agitator energy efficiency is sensitive to the impeller off-bottom clearance and impeller diameter, as reviewed by[5–9] among others. It should be noted that most of these studies were concerned with Newtonian slurry, with low viscosity, and operations at relatively low-solids concentration, typically in the range $\ll$ 20% (v/v) and almost always with baffles installed.

The aim of this article is to explore agitator and tank design methods to achieve increased product throughput through operating the slurries at high solids concentrations. Emphasis will be placed on modifications on large-scale existing tanks in minerals processing plants to increase the yield with the same equipment size, although the concept is applicable to develop smaller units at the design stage for achieving the same throughput. Newtonian, low-viscosity settling slurries at high solids concentrations are considered.

Experimental Setup

The mixing rigs (Figure 2a) consisted of a 390 mm diameter tank and a 1000 mm diameter tank, both with flat bottoms placed inside rectangular outer glass/acrylic tanks. The outer tanks were filled with water to minimize optical distortion.

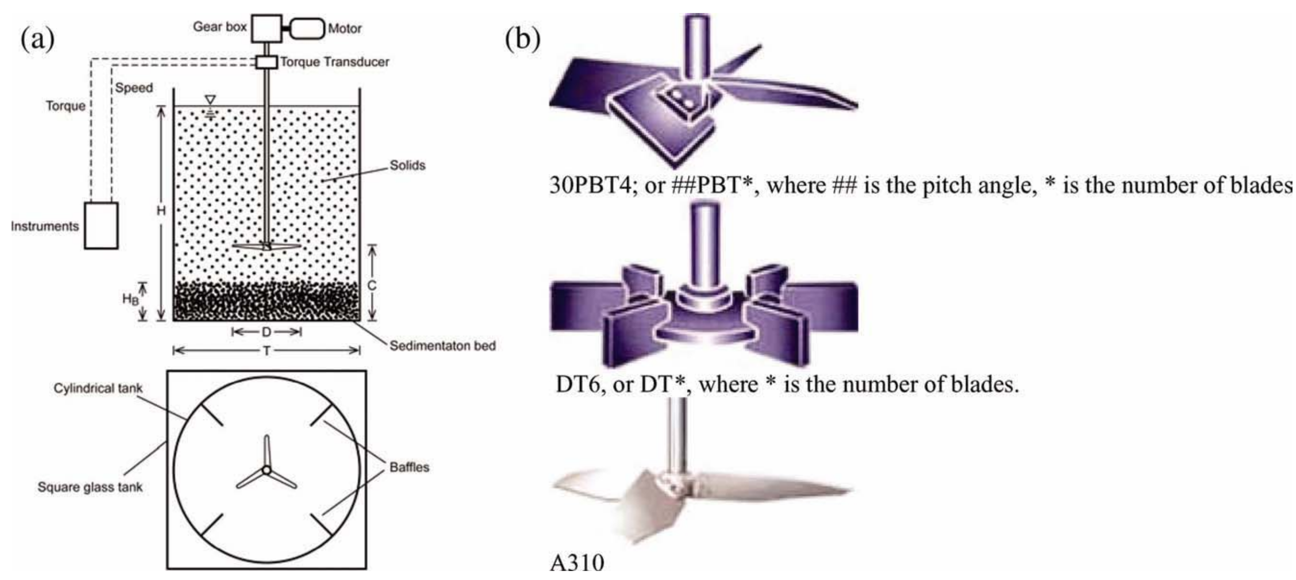

Figure 2. Mixing tank laboratory experimental setup, (a) test tank diameter 0.390 m and 1.0 m; (b) impeller examples, note that the impellers used may be a variation of these examples, in the actual number of blades, pitch angle.

Disk turbines and pitch bladed impellers used in 0.390 m tank: diameter 0.160 m, blade width 1/5 of diameter. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 1. Solids Properties

Type	Glass Beads
d_{10}	0.110 mm
d_{50}	0.165 mm
d_{90}	0.235 mm
Density	2500 kg/m^3

Four baffles 1/12 of tank diameter in width, equally spaced and with no gap to the wall surface, were installed in the circular tanks. Test impellers were mounted on the central shafts, which were equipped with Ono Sokki torque transducers and speed detectors. The speed and torque were logged using a personal computer equipped with a data acquisition board, and provided on-line analysis of power consumption.

Impellers used in the tests included pitch-bladed turbines, disk radial turbines, and axial flow hydrofoil impellers. Some examples of these impellers are shown in Figure 2b, where 30PBT4 means 30°, pitch bladed turbine with four blades, DT6 means six-bladed disk turbines, a Lightnin A310, and a CPE RTF4 are both hydrofoil axial flow impellers. Other similar impellers including 30PBT6, 45PBT4, DT3, and DT4 were also used, with their definition similar and self-evident. All impellers were installed at a nominal distance to the tank bottom at $\sim T/3$, where T is the tank diameter, unless stated otherwise.

Round glass particles were used in the experiments. Water was used as the fluid. The slurry properties are listed in Table 1.

The liquid/solids flow in the tank bottom was studied visually through the transparent tank walls and through the tank floor. Traditionally, the just-off-bottom suspension condition has been defined as no solids remain stationary at the bottom for more than 1–2 s, originally due to Zwietering.[10] In practice, this method is rather problematic, for example a single particle (or a small quantity) stationary in a corner may not be suspended even at very high-agitator speeds; thus, it is rather meaningless and unreliable to rely on the status of a small quantity of particles to determine the just off-bottom suspension condition. As an alternative approach,[11] the sedimentation bed height denoted as H_B was recorded vs. the speed, as the impeller speed was reduced from a full solids suspension condition (at higher speeds). The just off-bottom speed N_{js} is defined at a point where $H_B = 0$.

The mixing rate was quantified by measuring the time required to homogenize the liquid phase, i.e., the mixing time t_m. This was carried out by injecting a salt tracer solution into the tank through a dip tube submerged below the liquid surface, and recording the salt concentration with time using conductivity probes placed at multiple locations in the tank. These locations were near the wall, at half-tank height and at just above the bottom of the tank.

The experiments were carried out in batch mode. This was justified on the basis that the through flow was very small in comparison with the mixing flow by the impeller in the context of the mineral processing tanks, as typically the residence time (approximately hours) with the through flow is an order of magnitude longer than the mixing time scale (approximately minutes).

Theoretical Analysis: Intensification at High Solids

Intensification methods

Multiple tanks in series (Figure 1) are frequently used in the mineral processing industry to extract metals from ore slurries. Processes such as leaching and precipitation typically use up to 10 or more slurry tanks in series to achieve the required residence time. An important parameter is the residence time of solid particles, denoted as t_s:

$$t_s = n\frac{\rho_s V C_v}{\rho_s Q C_{v\_feed}} = t\frac{C_v}{C_{v\_feed}} \tag{1}$$

where V (m^3) is the volume of a single tank, Q (m^3/s) is the slurry flow rate, n is the number of tanks in series, ρ_s is the solids concentration (kg/m^3), C_v (v/v) is the averaged solid concentration in the tank, C_{v_feed} (v/v) is the solid concentration in the feed and discharge streams, assuming that a steady state is established, such that the solid concentrations of the feed stream and the discharge stream are equal. $t = nV/Q$ is the bulk slurry mean residence time. Note t_s is not necessarily equal to t. The solids mass flow rate (or throughput in a production term) is expressed as:

$$\dot{M}_s = \rho_s Q C_{v\_feed} \tag{2}$$

The purpose here is to explore intensification methods to boost the yield of metal extraction. Given n and V (number of tanks and the tank volume) and referring to Eqs. 1 and 2, there are two methods which can be suggested to boost the yield.

Method 1: Increased Solids Loading. Increase C_{v_feed} and C_v, whereas keeping the ratio of C_v/C_{v_feed} constant; This increases the solids mass flow rate, without altering the solids residence time t_s nor the slurry flow volume rate Q, refer to Eq. 2.

Method 2: Solids Stratification. This approach can be expressed as:

$$t_s > t \quad \text{for} \quad C_v/C_{v\_feed} > I \tag{3}$$

Increase the solids concentration in tanks to be higher than in the feed, i.e., increase the solids loading ratio C_v/C_{v_feed}, such that the solids residence time t_s is longer than the superficial residence time t.

This situation can be utilized to achieve an increase of solids mass flow rate (thus plant throughput) by increasing Q, as maintaining the same solids residence time. Alternatively, the solids residence time t_s can be increased proportionally to improve metal recovery for certain processes, as maintaining the same slurry flow rate Q. Either of these two approaches can be explored, depending on the process conditions.

Results

Upper limit of solids concentration

To achieve the purpose of intensification using high solids loading and the solids stratification method as outlined in the previous section, it is important to investigate operational

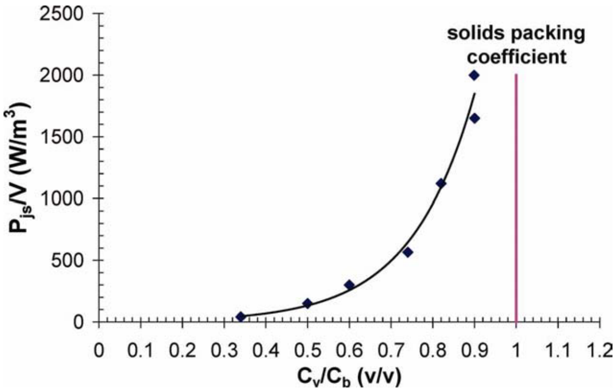

Figure 3. Specific power consumption vs. normalized solids concentration, at just off-bottom solids suspension condition, mixing tank diameter 0.39 m, liquid height 0.390 m, solids: glass particles of d = 0.09–0.15 mm, fluids: tap water.

Turbine: 30 PBT6, Impeller diameter 0.160 m, blade width 1/5 of diameter, 4× baffles, with 1/12 tank diameter width. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

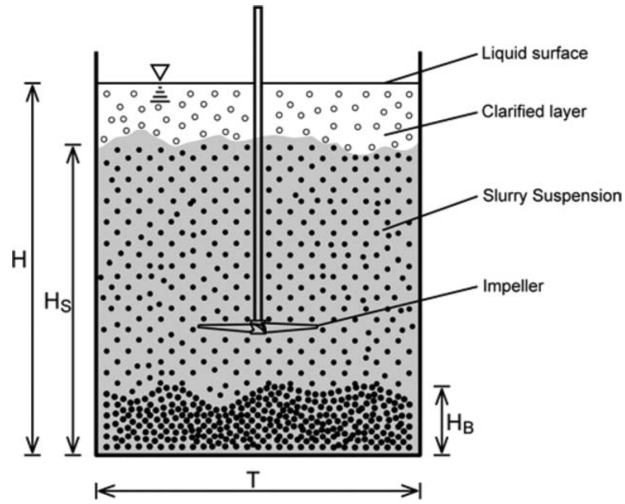

Figure 4. Solids suspension in tanks, with stratification, formation of a clarified layer at the top.

characteristics of a tank with the maximum possible solids concentration, achieved with mechanical agitation.

Figure 3 shows a test result 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 solid volume concentration C_v (v/v in the tank, normalized by C_b, the solids packing coefficient*), for the 30PBT6 impeller. Refer to the caption of the figure for more detailed description of the test conditions. It can be seen that the power required for just off-bottom suspension increased rapidly as C_v/C_b approaches 0.85–0.90. This corresponds to $C_v = 0.50$–0.55 for a packing coefficient of $C_b = \sim 0.60$ for the solid particles. It becomes practically impossible to go far beyond this value, due to a drastic increase in the motor power requirement.

It is prudent to consider $\frac{C_v}{C_b} \approx 0.90$ as the upper limit of the solids concentration for practical applications.

Stratification as a method to increase solids retention time

Referring to Eq. 3, having $t_s > t$ brings major benefits of either allowing higher solids throughput without affecting the solids residence time, or increased extraction recovery for the same slurry flow rate. This can be achieved by operating the solids suspension in tanks with stratification, such that the tank has a lower solids concentration at the top and a higher solids concentration at the bottom, as schematically illustrated in Figure 4.

In practice, stratification can be achieved by operating the tank such that the slurry cloud height is below the liquid surface:

$$H_s < H$$

where H_s is the slurry cloud height and H is the total liquid height in the tank (Figure 4). The slurry cloud height is loosely defined by the visual interface, occurring at a layer between the dense slurry suspension below, and light low-concentration slurry above. Refer to Hicks et al.[13] for an earlier study on this parameter.

Measurements through taking samples suggest that the solids concentration typically changes abruptly across the interface dividing the two zones,† and that the concentrations within both zones are practically constant (being at a low value in the top zone and a high value in the bottom zone).

The feasibility of operating the tank with stratification was investigated by conducting a set of solids suspension experiments in the 390 mm diameter mixing tank, using a pitch bladed turbine (30PBT6) and a radial turbine DT6.

Figure 5 shows the sedimentation bed and slurry cloud height as a function of speed of the pitch bladed turbine (30PBT6). It can be seen that sedimentation bed height decreases, whereas the slurry cloud height increases as the speed increases, as expected. It can be seen from Figure 5 that it is possible to operate the tank with a slurry height H_s less than the liquid height, and still maintaining good off-bottom suspension. Within the speed range of 220–450 rpm, solids are fully suspended from the tank bottom, i.e., $H_B \geq 0$, but the solids suspension height is lower than the normalized full liquid height ($H_s/H < 1$).

This suggests that it is possible to operate in a speed range achieving both off-bottom suspension and stratification in the tank. It should be mentioned that the degree of stratification is also a function of the impeller size, impeller location, liquid height, and other parameters, and more experiments are required to characterize these effects.

High solids concentration at improved energy efficiency

It is necessary to investigate methods to improve the agitator energy efficiency at high solids concentrations, due to associated higher power consumption. Tests were initially conducted at a solids concentration of $C_v = 0.40$ (v/v) in the 1000 mm tank, to explore various agitator design options to minimize the power required to suspend solid particles off the tank bottom. Lightnin A310 impellers and CPE RTF4 impellers, all pumping downward, were used in the tests.

*The packing coefficient is defined as the volumetric solids concentration of settled solids without mechanical consolidation by, e.g., vibration.

†For homogeneous particle size.

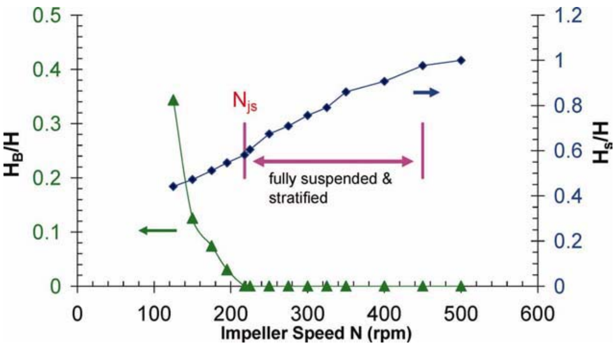

Figure 5. Sedimentation bed and slurry height vs. speed.

Impeller: 30PBT6, pitch bladed turbines, number of blades 6. Impeller diameter 160 mm; 80 mm to tank bottom, tank diameter 390 mm, liquid height 420 mm. Solid particles $d_{50} = 105$ μm, SG = 2.52, concentration $C_v = 0.20$. Fluid: water. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 6 a shows the effect of impeller diameter change on curves of sedimentation bed height (normalized by H) vs. the power per solids mass (P/M_s), where H_B is the sedimentation bed height, H is the liquid height, P is the power, and M_s is the total solids mass in the tank. The just-off bottom solids condition was reached when $H_B = 0$, i.e., $N = N_{js}$ and $P = P_{js}$, where the subscript "js" refers to "the just off-bottom suspension condition." It can be said that the effect of impeller diameter change is marginal on P_{js}/M_s, i.e., the power per solids mass required to suspend the solids from the bottom, albeit at this high solids concentration. Figure 6b shows the effect of changing impeller type, where the essential difference between A310 and RTF4 is that the former has a higher power number (with three blades, $P_0 = 0.31$) and the latter has a lower power number of 0.16 (four blades), whereas both use hydrofoils and are equally efficient in terms of pumping.[11] It is evident that the usage of a low power number impeller led to increased power consumption to suspend solids particles from the tank bottom at the current high solids concentration (0.40 v/v).

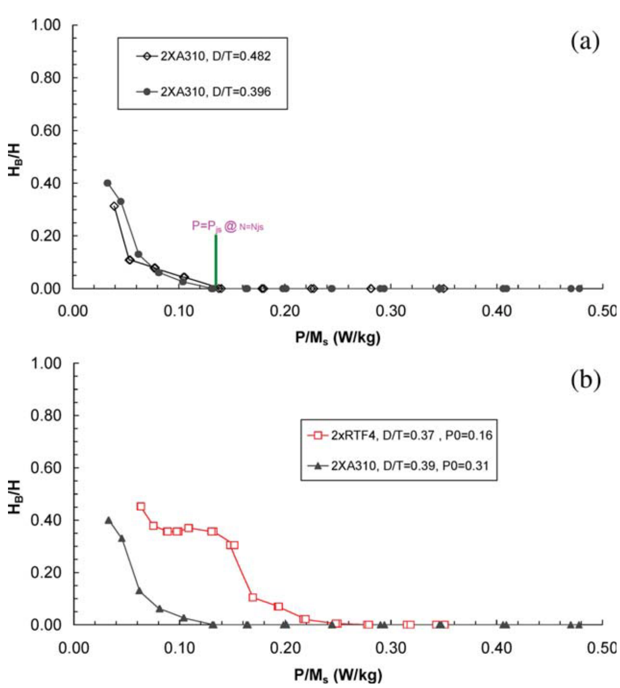

Figure 6. Settled solids bed height vs. agitator power.

(a) Effect of diameter change on power, (b) effect of impeller type. Solids loading $C_v = 0.40$ (v/v), agitator: 2× Lightnin A310, 3-bladed axial flow impellers, 2× CPE RTF4 4-bladed axial flow impellers, pumping downward, bottom impeller located at 0.4 m from tank bottom, impeller spacing 400 mm, liquid height 1150 mm, tank diameter 1000 mm, impeller diameter 482 mm, 396 mm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

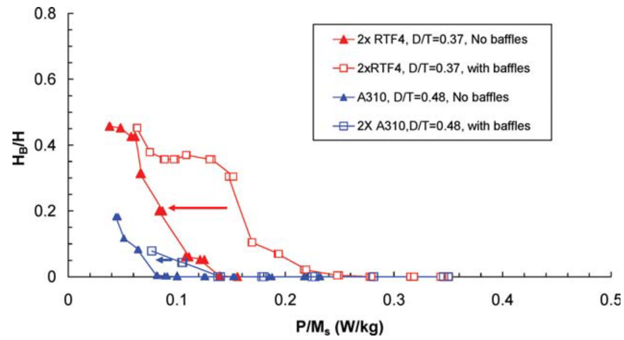

Figure 7. Settled solids bed height vs. agitator power: effect of baffle removal.

Solids loading $C_v = 0.40$ (v/v), agitator: 2× Lightnin A310, 3-bladed axial flow impellers, 2× CPE RTF4, 4-bladed axial flow impellers, pumping downward, bottom impeller located at 4000 mm from bottom, impeller spacing 400 mm, liquid height 1150 mm, tank diameter 1000 mm, impeller diameter 482 mm, 396 mm (A310), and 370 mm (RTF4). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 7 shows the effect of removal of baffles. It is evident that there is trend of lower power consumption (highlighted by the arrows) for the sedimentation bed curves as baffles are removed.

The power required at the just off-bottom condition is defined as:

$$\varepsilon_{js} = \frac{P_{js}}{M_s} \tag{4}$$

where ε_{js} is the specific power (W/kg), P_{js} is the agitator power, and M_s is the mass of solid particles (kg) in the tank. The specific power ε_{js} data are listed in Table 2. It can be estimated from the table that, for both A310 and RTF4 impellers, the power required to just suspend solids P_{js} decreased ~40%, at a solids concentration of $C_v = 0.40$ (v/v), when the baffles are removed.

Tests were repeated in a smaller tank, 390 mm in diameter, at the same solids loading of 0.40 (v/v). Figure 8 shows

Table 2. The Effect of Baffle Removal on the Specific Power $\varepsilon_{js} = P_{js}/M_s$, Based on Figure 6, Tank Diameter 1000 mm

	With Baffles	Baffles Removed	% Change With Baffles Removed
2× A310	0.14	0.08	−42%
2× RTF4	0.25	0.15	−40%

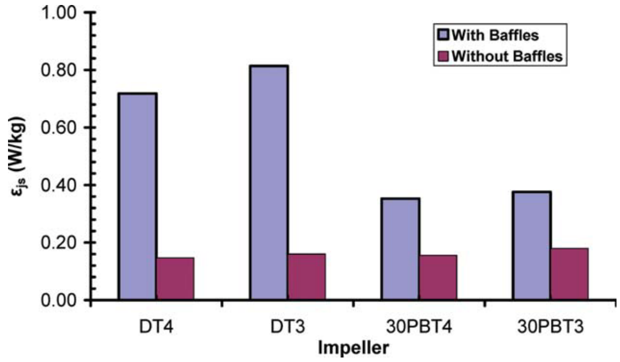

Figure 8. Specific power at the just off-bottom solids suspension condition at a solids loading of 0.40 (v/v).

Impeller diameter $D = 0.16$ m, $C/T = 1/3$, $H/T = 1$, $T = 0.39$ m. Fluid: Water. Glass particles water slurry, particle size 0.09–0.15 mm, SG = 2.5. (a) Baffles installed; (b) without baffles. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

a comparison of the specific power required to just suspend solids off-bottom in the 0.390 m tank using pitch-bladed turbines and radial disk turbines, with and without baffles.

It can be seen that, with baffles installed, it is more energy efficient to use axial flow impellers than radial flow impellers to suspend solids. With baffles removed, a dramatic reduction in power is achieved for both axial and radial flow impellers, consistent with the previous findings. It is interesting to note that radial impellers showed a greater reduction in the power consumption as in comparison with the axial flow impellers. The former recorded ~80% reduction, whereas the latter ~52–56%, as outlined in Table 3, based on Figure 8. It can be seen that radial flow impellers are marginally more energy efficient than axial flow impellers for suspending solids, with baffles removed, at $C_v = 0.40$ (v/v).

It can be estimated based on Table 3, the four-bladed turbines (DT4, 30PBT4) consume ~10% less power than the three-bladed turbines (DT3, 30PBT3), for both baffled and unbaffled conditions. This is consistent with the earlier finding that a high power number impeller is more energy efficient than a low power number impeller, at the current high solids concentration.

It can be commented that the reduction in power consumption by removing baffles at the just-off bottom condition is more dramatic for radial flow impellers, less for axial flow impellers, particularly for hydrofoil impellers (e.g., A310, RTF4). This is probably expected as hydrofoil impellers are usually more energy efficient than other impellers for suspending solids if baffles are installed.

Table 3. The Effect of Baffle Removal on the Specific Power $\varepsilon_{js} = P_{js}/M_s$, Based on Figure 8

	Power Number (With Baffles/Water)	With baffles	Baffles Removed	% Change With Baffles Removed
DT4	4.10	0.72	0.15	−80%
DT3	3.20	0.82	0.16	−80%
30PBT4	0.66	0.35	0.16	−56%
30PBT3	0.53	0.38	0.18	−52%

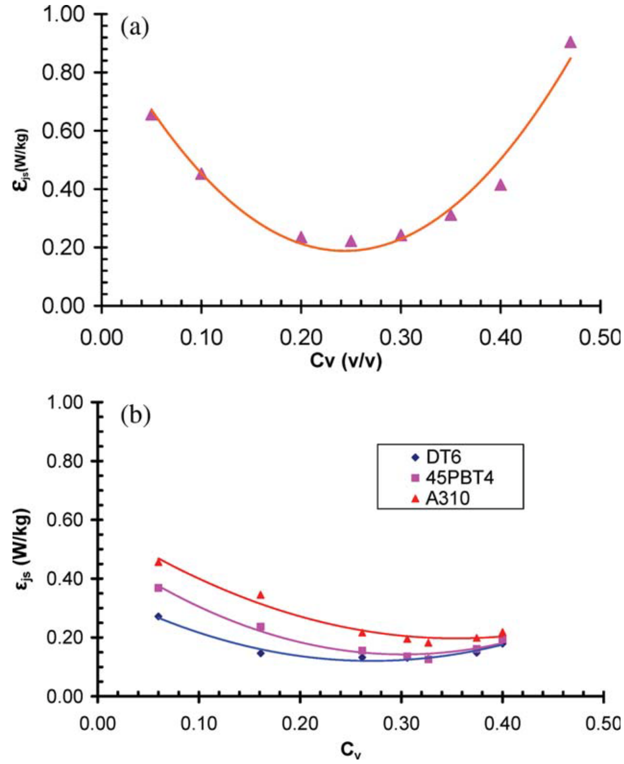

Figure 9. Specific power consumption vs. solids concentration, at just off-bottom solids suspension condition, mixing tank diameter 0.39 m, liquid height 0.390 m, solids: glass particles of d = 0.09–0.15 mm, fluids: tap water.

Impeller diameter 0.160 m, (a) with baffles ×4, with 1/12 tank diameter width, impeller 30PBT6 (b) without baffles. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 9 a shows ε_{js} as a function of solids concentration, with baffles installed. It can be said that the best solids suspension agitation energy efficiency can be achieved at medium solids concentration of ~0.25 (v/v). Nevertheless, operating at higher concentration, say 0.40 (v/v) can still be justified, if the benefits of increased throughput are weighed against the increased energy cost.

Clearly, operating at a solids loading $\ll 0.2$ (v/v) is very wasteful, for both lower energy efficiency, and lower utilization of tank facilities. Unfortunately, it is still not uncommon to see slurry tanks operating at such low solids loadings in the mineral industry.

Figure 9b shows ε_{js} vs. solids concentration for different impeller types, with baffles removed. It can be seen that there is a broad decreasing trend of the specific power as the solids concentration is increased toward 0.25–0.35 (v/v) for all the impeller types tested. Although still visible, the minimums are less significant as in comparison with that in Figure 9a where baffles are installed. It is also interesting to comment that the minimums occur in the region of 0.25–0.35 (v/v) with baffles removed, higher than that occurred at 0.25 (v/v) with baffles installed.

Figure 9b reinforces a feature mentioned early (refer to Table 3) that the radial flow impeller (i.e., DT6, 6-bladed disc turbine) is more efficient than A310 a widely used axial flow impeller, when baffles are removed.

Mixing performance with baffles removed

Both dispersion of the solid phase and mixing of the liquid phase are required for most slurry reactors, except for slurry holding tanks in a mineral processing plant. A full dispersion of solids corresponds to a good utilization of the tank volume. A good mixing of the liquid phase exposes the ore particles to fresh chemical solution.

Dispersion of solids is conveniently quantified by the solids suspension cloud height, H_s, as mentioned before. Liquid phase mixing tests were carried out by conducting saline tracer tests.

Figures 10a, b show the normalized slurry cloud height (H_s/H) as a function of the specific power, with/without baffles at 40% (v/v) of solids concentration, for the radial flow disc turbine DT6 and the axial flow pitch bladed turbine 30PBT6. Sedimentation bed curves are included for comparison.

It can be seen that there is a shift toward lower power consumption when baffles are removed for both DT6 and 30PBT6. This suggests that a lower specific power is required to provide dispersion of solids without baffles, similar to that for off-bottom solids suspension. It can be therefore stated that it is more energy efficient to remove baffles for dispersing solids to higher slurry height.

It is also interesting to note that operating with stratification in the fully off-bottom solids suspension condition is feasible when baffles removed at $C_v = 0.40$ (v/v), i.e.:

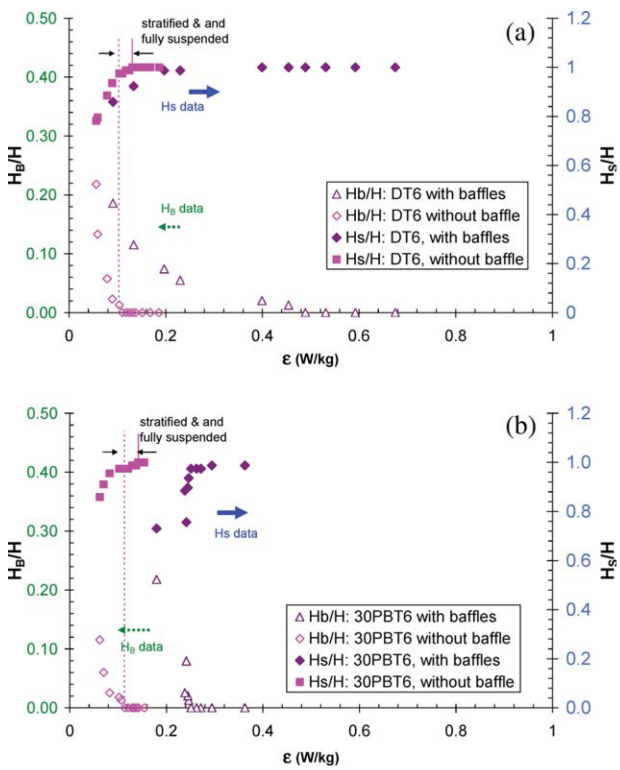

Figure 10. Baffle effect on solids dispersion: slurry height vs. specific power, together with sedimentation bed curves as reference, (a) DT6, (b) 30PBT6.

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

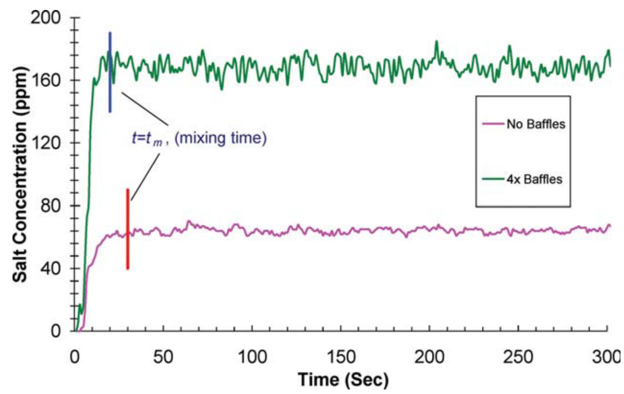

Figure 11. Mixing time measurements: the effect of baffles.

The agitator design with an A310 at the bottom, $D/T = 0.48$, and an RTF4 at the top, baffles installed or removed; tank diameter $T = 1.0$ m, liquid height 1.15 m, baffles removed, solids loading 40% (v/v). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$$H_s < H$$
$$H_B = 0$$

However, with baffles installed at the current high solids loading of 40% (v/v), it is difficult to produce stratification, whereas still maintaining off-bottom solids suspension. For example, as evident from Figure 10a, for $H_B \geq 0$, $H_s/H = 1$, suggesting no stratification with this test configuration using DT6. For 30PBT6 shown in Figure 10b, a rapid change in H_s/H can be seen in the vicinity of $H_B = 0$, suggesting essentially an uncertain status of stratification.

This is different from that shown in Figure 5, where at a solids loading of 20% (v/v) with baffles, distinctive stratification was produced by a 30PBT6. Subject to further studies, it can be commented that with increased solids concentration (from 20% v/v to 40% v/v), it becomes more difficult to produce stratification.

The effect of removal of baffles on the liquid phase mixing time is shown in Figure 11 as an example. The time started at the moment the tracer salt solution was injected. The salt concentration increased and approached an asymptotic level (albeit with some fluctuations) after a period of time defined as the mixing time. It can be seen that the mixing time increased from $t_m \approx 20$ s with baffles installed to approximately $t_m \approx 30$ s, after the baffles were removed.[‡] It is perhaps expected that the mixing rate would be lower due to an apparent whole body rotation of the slurry upon removal of the baffles. However, underneath the superficial rotation upon baffles removed, there was sufficient mixing such that a homogeneous salt concentration state would be reached after a period of time, albeit longer than with the baffles installed.

Intensification case example

To illustrate the benefits of process intensification via operating with an increased solids concentration, a case example

[‡]A shift in the background asymptotic level of the salt concentration was caused by build up of salt after the initial experiments.

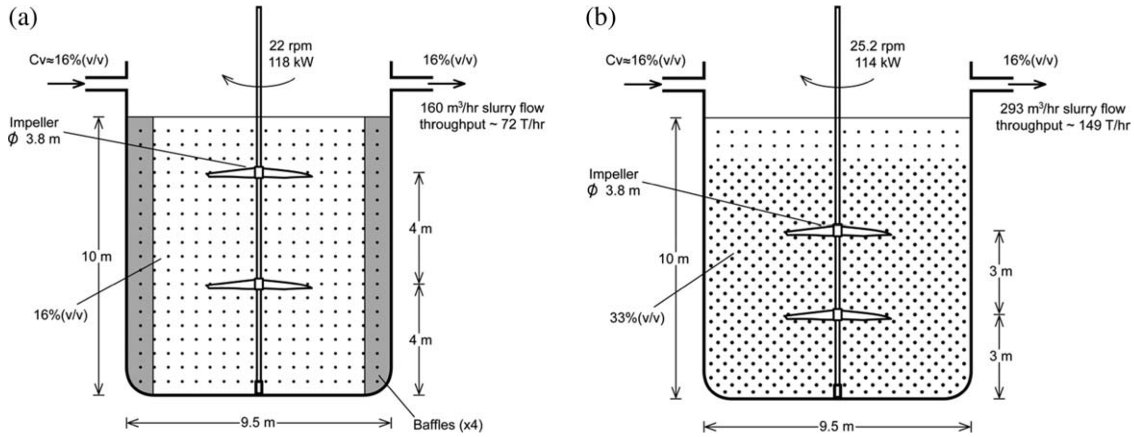

Figure 12. Intensification case illustration, (a) existing design, throughput 72 T/h, (b) improved design with throughput 149 T/h.

based on a full-scale leaching tank in a mineral processing plant is illustrated in Figure 12, and its parameters listed in Table 4.

Refer to the existing design, three slurry tanks (in-series) with diameter of 9.5 m and height of 10 m were used for a continuous leach operation with a solids mass throughput of 72 T/h at a design residence time of $\sim$13.3 h, which is required for a complete metal extraction.

The new design, which was developed with baffles removed, the agitator speed increased and operated at a higher in tank solids concentration of 0.33 v/v, significantly higher than that used in the current design (0.16 v/v), which is also equal to the feed concentration. Note that the agitator power with the new design is essentially same as that of the existing design, even with a substantial increase of the shaft speed, due to removal of baffles. Also it should be pointed that the agitator locations were lowered, to produce a good stratification result. Note that the solids retention time ($\sim$13.3 h) is longer than the bulk slurry flow residence time ($\sim$6.4 h) with the new design.

It can be seen that an increase of product solids throughput from 72 T/h to 149 T/h is achieved with the new design, operating with the same solids residence time. This represents a massive +107% increase in the product throughput (i.e., the solids particles mass flow) at essentially the same power input, with little capital investment, and minimum design changes including removal of baffles, and a gearbox retrofitting for a speed upgrade.

Discussion

For slowly reacting slurry systems typical in the mineral processing operations, where reaction kinetics is not diffusion-limited, i.e., chemical reaction rate being significantly slower than the physical diffusions influenced by the fluid dynamics, it is sufficient to design the agitation based on off-bottom solids suspension. Such chemical reactions can be maintained so long as there is sufficient contact of solids with the liquid phase, which can be achieved by maintaining solids suspension off tank bottom.

The slow kinetics could be further explored by operating at high solids concentrations and even with solids stratification in tanks. This will lead to increased throughput, thus achieving our purpose of process intensification-increased production yield for the same tank volume infrastructure.

A key hurdle with operating at a very high solids concentration is large agitation power consumption. Excessively larger power consumption is particularly problematic for minerals processing plants, where large-scale agitator equipment means demand for larger motor and gear box equipment becoming hurdles to the attempts to increase the solids loadings. To enable operating at very high solids concentration, it is extremely desirable to use methods to improve agitator energy efficiency at high solids loadings.

Removal of baffles as shown in this article is a very effective way to drastically reduce the specific power for suspending solids particles off the tank bottom. This method can be used to significantly improve the energy efficiency of operating slurry tanks. It is interesting to comment that radial impellers are found to be not noticeably less energy efficient (or even slightly more efficient) than axial flow impellers for suspending solids when baffles are removed, in contrast to the conventional knowledge that axial flow impeller

Table 4. Case Example Based on a Full-Scale Mineral Leaching Tank, Effect of Process Intensification

Parameters	Existing Design	New Design
No. of tanks	×3	×3
Tank diameter	9.5 m	9.5 m
Tank liquid height	10 m	10 m
Baffles	×4 vertical	Removed
Agitator	2× 45PBT4	2× 45PBT4
Agitator diameter	3.8 m	3.8 m
Agitator speed	22.0 rpm	25.2 rpm
Speed margin above N_{js}	+10%	+10%
Agitator power	118 kW	114 kW
Liquid density	1000 kg/m^3	1000 kg/m^3
Solids density	2820 kg/m^3	2820 kg/m^3
Particle size d_{80}	70 μm	70 μm
Solids concentration in tank	0.16 (v/v)	0.33 (v/v)
Slurry bulk flow	160 m^3/h	293 m^3/h
Product solids throughput	72 T/h	149 T/h
Solids residence time	13.29 h	13.31 h
Bulk flow residence time	13.29 h	6.44 h

more efficient than radial impellers, albeit for suspending solids with baffles installed.

With baffles removed, it is easy to produce solids stratification, because a lower agitation level can be used with a dramatic power reduction for off-bottom solids suspension. Thus, removal of baffles could be used for process intensification via solids stratification (Method 2). It is also noted that there is a general trend of reduction in the specific power for a given slurry height, suggesting reduced power consumption for a given solids dispersion.

Because typically a great many large-scale slurry tanks are used at a mineral processing plant, such improvement can provide a major economic saving to the owner companies. A side effect with baffles removed is increased mixing time. This is usually not a problem in the mineral processing industry, where the time scale for reactions, and the slurry residence time are typically an order of magnitude larger than the mixing time.[§] Mixing is not required in some tanks, e.g., slurry holding tanks where the slurries are held to smooth out the fluctuations in the slurry flow rate, occurring due to variation of throughput in other unit operation equipments in the continuous slurry flow circuit.

In passing, it is worthwhile to discuss the benefit of increased residence time (t_s), as suggested in Method 2. In certain metal refining reactions, increased solids residence time leads to increased yield. For instance, in an alumina hydrate precipitation process, additional growth of alumina crystals can be achieved through increased particle residence time.

Conclusions

The concept and equations of using high solids concentration for process intensification are outlined. It can be stated that high solids concentration and stratification in tanks lead to increased throughput. For slowly reacting slurry systems in mineral processing operations, it is sufficient to design the agitation based on off-bottom solids suspension. Improved energy efficiency is critical for operating at high solids concentration. This can be achieved by using large power number impellers, and removal of baffles. Radial flow impellers are more energy efficient for off-bottom solids suspension, when baffles are removed. Solids dispersion and stratification can be quantified using the slurry cloud height. The feasibility of producing stratification whilst maintaining off-bottom solids suspension is demonstrated. The benefits of process intensification is illustrated by a case study based on full-scale designs, which showed +107% increase in the throughput with a relatively simple design change, with no change in the power requirement.

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Notation

C = impeller to tank bottom distance, m
C_b = solids packing coefficient, v/v
C_{v_feed} = solids volume concentration in the feed pipe, v/v
C_v = solids volume concentration in tank, v/v
D = impeller diameter, m
H = liquid level, m
H_B = settled bed height, m
H_s = slurry height, m
M_s = solid particles mass in tank, kg
$\dot{M}_s$ = solid particles mass rate in tank, kg/s
n = number of tanks
N = impeller speed, rev/s, rpm
N_{js} = just-off bottom solids suspension speed, rev/s, rpm
Q = slurry flow rate, m^3/s
P = power, W
P_0 = impeller power number
P_{js} = power at just-off bottom solids suspension condition, W
T = tank diameter, m
t = bulk slurry flow residence time, s
t_s = solids residence time, s
t_m = mixing time, s
V = slurry volume in tank, m^3
ε_{js} = power per solid mass at just off-bottom solids suspension condition, W/kg
ρ = solid density, kg/m^3

Literature Cited

1. Wu J, Graham LJ, Mehidi MNN. Intensification of mixing. *J Chem Eng Jpn*. 2007;40:890–895.
2. Wu J, Graham LJ, Nguyen B. Mixing intensification for the mineral industry. *Can J Chem Eng*. 2010;88:447–454.
3. Drewer GR, Ahmed N, Jameson GJ. Suspension of high concentration solids in mechanically stirred vessels. IChemE Symp. 1994; Series 136:41–48.
4. Wu J, Zhu Y, Pullum L. Suspension of high concentration slurry. *AIChE J*. 2002;48:1349–1352.
5. Nienow AW. *The suspension of solid particles*. In: Hamby N, Edward MF,Nienow AW, editors. *Mixing in the Process Industries*. London: Butterworths, 1992.
6. Ibrahim S, Nienow AW. Particle suspension in turbulent regime: the effect of impeller type and impeller/vessel configuration. *Trans IChemE*. 1996;74:679–688.
7. Chapman CM, Nienow AW, Cook M, Middleton JC. Particle-gas-liquid mixing in stirred vessels. I. Particle-liquid mixing. *Chem Eng Res Des*. 1983;61:71–81.
8. Wu J, Zhu Y, Pullum L. Impeller geometry effect on velocity and solids suspension. *Trans IChemE*. 2001;79(A):989–997.
9. Nienow AW. The dispersion of solids in liquids, mixing of liquids by mechanical agitation. In: Ulbrecht J, Patterson GK, editors. *Chemical Engineering: Concept and Reviews*. New York: Gordon and Breach Science Publishers, 1985.
10. Zwietering TN. Suspension of solids in liquid by agitators. *Chem Eng Sci*. 1958;8:244–253.
11. Wu J, Graham LJ, Nguyen B, Mehidi MNN. Energy efficiency study on axial flow impellers. *Chem Eng Process*. 2006;40:625–623.
12. Wu J, Nguyen B, Graham LJ. Energy efficient high solids loading agitation for the mineral industry. *Can J Chem Eng*. 2010;88:287–294.
13. Hicks MT, Myers KJ, Bakker A. Cloud height in solids suspension agitation. *Chem Eng Commun*. 1997;160:137–155.

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[§]Example for a gold leaching process, 20–40 h leaching residence time is not uncommon, whereas the mixing time is at an order of 5–10 min.