# Mixing Technology for Buoyant Solids in a Nonstandard Vessel

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The use of nonstandard vessels with aspect ratios (liquid-depth to tank-diameter ratio) greater than one is not uncommon in chemical and biochemical process industries (Hicks and Gates, 1975; Pollard and Topiwala, 1976). Similarly, the mixing of buoyant particles, which may include either solids or immiscible liquid droplets, in a carrying liquid is encountered in quite a number of process industries, for example, polymer, pharmaceutical, paint, and food industries. In these processes, mixers are used to draw down buoyant particles for a variety of reasons, for example, chemical reactions including catalysis, coagulation, dissolution, ion-exchange, adsorption, crystallization, and precipitation. In addition, mixers are designed to overcome the mechanical problem of slurry withdrawal from a vessel. In all these operations, the fluid motion is turbulent and the particle concentration is usually low so as to have a negligible effect on fluid viscosity. Consequently, good mixing is very important since poor mixing can lead to local variations in concentration causing poor product quality.

Despite its numerous applications, mixing of buoyant solids has not drawn as much an interest within the research community as its counterpart case of heavier solids dispersed in liquids. Joosten et al. (1977) examined the influence of vessel geometry and impeller type on the minimum stirrer speed and associated power consumption required to drawdown floating solids in a standard tank. Edwards and Ellis (1984) studied the influence of baffle number, stirrer type, solids mass fraction, and bottom clearance on drawdown of buoyant solids. They observed no effect of solid concentration on minimum speed for drawing down solids at low solids mass fractions. Hemrajani et al. (1988) studied the influence of baffle arrangement on minimum tip speed needed for drawdown of buoyant particles. Bakker and Frijlink (1989) studied mixing under gassed conditions in a fully baffled stirred tank. Thring and Edwards (1990) investigated the effect of baffle configuration, type of impeller, solids concentration, and impeller clearance on the minimum drawdown speed and associated power input. Solids concentration and impeller clearance had a small effect on the minimum drawdown speed. Even these few studies that dealt with this subject, did not consider the case of mixing in a nonstandard vessel with aspect ratios greater than 1.2.

Conventional mixer designs, employing four fully immersed baffles, have been found to be inadequate for buoyant particles (Joosten et al. 1977; Smith and Tarmy, 1979; Hemrajani et al., 1988). The omission of the baffles, on the other hand, leads to a poor distribution of the solids over the vessel contents. The solids tend to concentrate near the vortex in the liquid. This led to the use of *partial baffles* which were found to be suitable for buoyant particles. Smith and Tarmy (1979) introduced partial baffles for drawing down buoyant particles. Partial baffles as the very name implies are baffles which are smaller than full baffles. Examples of several types of partial baffles are given in Smith and Tarmy (1979) and Hemrajani et al. (1988). These include the full length narrow baffles (width $= T/50$), rectangular and triangular finger baffles positioned at the liquid surface. In this note, we report the results of extensive experiments using partial baffles for incorporating buoyant particles in a nonstandard vessel.

## Scale-up Considerations

Following Rushton et al. (1950), the motion of solid particles in a fluid agitated with a mechanical agitator with a speed $N$ may be expressed as follows:

$$N_p = \text{function of } (N_{Re}, N_{Fr}; \phi, x, S) \tag{1}$$

where $S$ is the lump parameter for the various shape factors.

A disadvantage of this set is that most of these dimensionless groups cannot be independently varied, thus complicating the analysis of the experimental data. By fixing certain quantities, for example, $\phi$, $x$, and $S$, however, the effect of other quantities can still be studied. When this is done, one can plot $N_p N_{Fr}^{\beta}$ as a function of $N_{Re}$ for a particular mixer and baffle geometry. Here, $\beta$ is a function of $N_{Re}$ and shape factor, $S$, and is written as

$$\beta = (\log N_{Re} - a)/b \tag{2}$$

where $a$ and $b$ are empirically determined constants for the particular mixer geometry.

In general, for scaling up geometrically similar vessels, the agitator speed is scaled as

$$N_2 = N_1 (D_1/D_2)^n \tag{3}$$

where $n$ is an exponent having a value between 0 to 1. For buoyant solids dispersed in a liquid, Hemrajani et al. (1988), however, suggested a value of 0.56 for scale-up with narrow $T/50$ baffles. (We also found the above value to be quite accurate in our experiments with four narrow $T/48$ baffles.)

## Experimental Work

Experiments were carried out in vertical, cylindrical plastic tanks having flat-bottoms and internal diameters of 0.15 to 0.203 m. The liquid height was maintained such that the aspect ratio was varied between 1 to 4. Polypropylene beads of equivalent diameter ranging from 0.2 to 0.35 cm and specific gravity of 0.91 were chosen as the solids. (A limited number of studies were also done with solids having significantly lower specific gravity.) The liquid used was a corn syrup solution having a viscosity of 10 mPa·s and a density of 1,020 kg/m$^3$.

Preliminary studies with polypropylene beads in corn syrup solution in an agitated, unbaffled tank confirmed the observations made earlier by Hemrajani et al. (1988). The liquid swirl provided the necessary mechanism for pulling down the buoyant solids into the bulk of the liquid. The centripetal forces arising out of the rotating motion of the impeller caused the buoyant particles on the liquid surface to move into the cone of the vortex. Inside the cone, the liquid velocity was high enough to incorporate the particles into the bulk of the liquid. These two steps, that is, the formation of a vortex and the transport of particles from the cone to the bulk of the liquid, were crucial for homogenization of the tank volume.

In unbaffled tanks, the mixing of buoyant particles requires the consideration for how the vortex depth may be influenced by the size of the tank. Zlokarnik (1971) showed that vortex depth is proportional to the square of the tip speed under turbulent agitation conditions ($N_{Re} > 3,000$). Therefore, if the tip speed is kept constant and the size of the tank is increased, vortex depth will still remain the same as in the smaller tank, but will be much smaller in proportion to the tank height. This small vortex may not be sufficient for incorporating the solids into the bulk of the liquid.

In our study, attention was given to two types of partial baffles, the full-length narrow baffles of width equal to 1/48th the tank diameter and partially immersed rectangular (finger) baffles. Our main objective in this selection was to compare the performances between these two types of partial baffles.

Two types of mixers, 4-blade 45° pitched-blade turbines (PBTs) and Lightnin A100 marine propellers, were used. The diameters and widths of the PBTs were varied between $T/3$ to $T/2$ and $T/16$ to $T/8$, respectively. The A100 propeller had a diameter of 0.079 m. The number and spacing between the mixers were varied depending upon the aspect ratio and for evaluating mixer performance. Usually, for every unit increment in aspect ratio, one additional mixer was used.

The tank was initially filled to a certain height with the liquid. Polypropylene beads (0.1 to 1 wt. %) were added to the liquid. The shaft rod with 1 to 4 mixers placed at various positions along its length was centrally mounted. Baffles of various

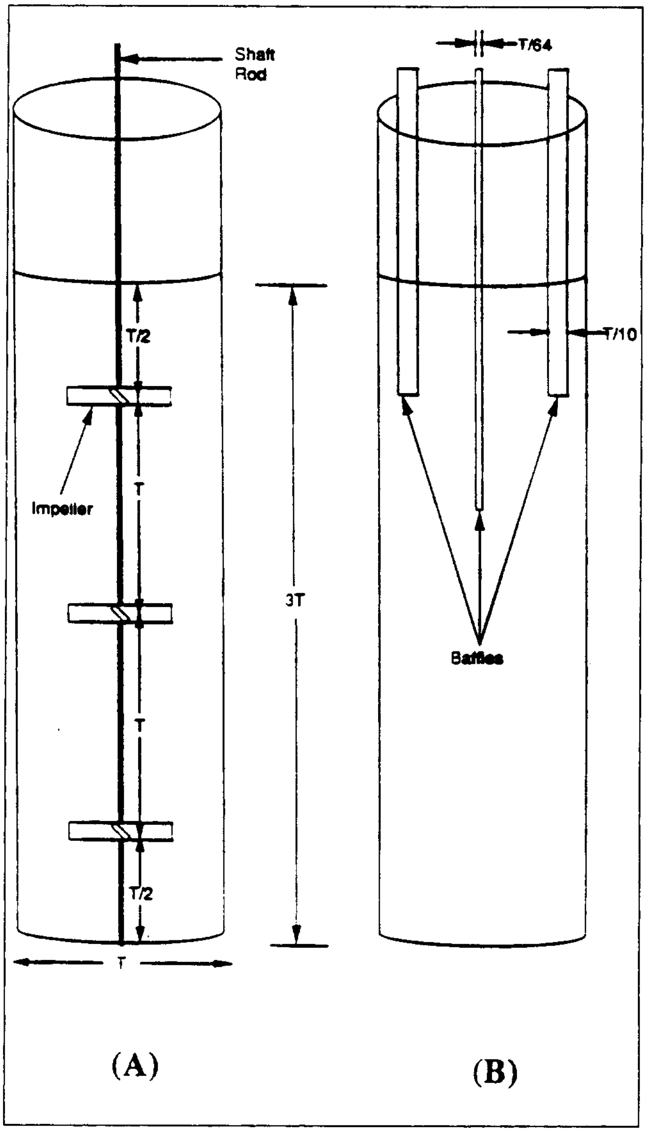


**Figure 1. Optimum (A) mixer and (B) baffle position for a tank of aspect ratio of 3.**

widths ($T/48$–$T/8$) and thicknesses ($T/64$–$T/48$) were either immersed partially at various positions along the circumference of the tank or were fully immersed inside the tank. The motor was started at a low speed and its speed was then gradually increased until an optimum speed (see below) and baffle or mixer configuration was found for the best drawdown of the solids. The power drawn was recorded with the aid of a wattmeter connected to the motor drive. (In our calculations for $N_p$, the net power required to draw solids was used by subtracting the frictional power load in an empty tank from the gross power draw.) After each set of experiments, the motor was stopped and the number and positioning of the baffles and mixers were varied to find the most optimum setting for mixer performance. Experiments were repeated several times for checking reproducibility of the results.

In our studies, we found the minimum (optimum) speed at which slurry homogeneity took place for the *entire* length of the tank. Slurry homogeneity is, however, very easy to define but extremely difficult to measure. The use of vertical colli-

Table 1. Effect of Baffling Configuration on Mixing with 3 PBTs at 300 rpm

| Baffle position | Spacing | Time to Homogenize(s) | Comments |
|---|---|---|---|
| None | | — | particles cling to shaft; very poor |
| 1 full immersion | $T/10$ | >60 | particles mostly in upper half |
| 1 @ $2T$ | do | 25–30 | poor mixing |
| 1 @ $3T/2$ | do | 20–25 | —do— |
| 1 @ $T$ | do | 16–20 | good mixing |
| 2 @ $T$ | 90° apart | 17 | good |
| 2 @ $3T/2$ | do | 45 | poor |
| 2 @ $2T$ | do | >60 | poor |
| 2 @ $2T$ | 180° apart | >60 | poor |
| 4 full | 90° apart | — | extremely bad |
| 3 full | 90° apart | >60 | very poor |
| 2 full | 90° apart | >60 | very poor |
| 2 full | 180° apart | >60 | very poor |
| 2 @ $T$ | 180° apart | 15 | good |
| 2 @ $T/2$ | 180° apart | 15 | very good mixing |
| 3 @ $3T/2$ | 90° apart | >60 | poor |
| 3 @ $T$ | 180° apart | 17 | good mixing |
| 3 @ $T/2$ | do | 13 | very good mixing |
| 2 @ $3T/2$, $T/2$ | 90° apart | 20–25 | good |
| 2 @ $3T/2$, $T$ | do | 25–30 | good |
| 2 @ $T$, $T/2$ | do | 15 | good mixing |
| 3 @ $T$, $T/2$, $3T/2$ | 90° apart | 30 | good |
| 3 @ $T$, $T/2$, $T$ | do | 15 | very good |
| 3 @ $T/2$, $T/2$, $T$ | do | 13 | very good |
| 3 @ $T/2$, $T$, $T$ | do | 15 | very good |
| 3 @ $T/2$, $T$, $T/2$ | do | 13 | very good mixing |
| 3 @ $T/2$, $3T/2$, $T/2$ | do | 20 | good mixing |

mated light beams and photographs (Nienow and Miles, 1978), conductivity probes (Musil, 1976), photodiode probes and infrared emitter-detectors (Ellis et al., 1988), and optical methods (Calderbank and Jones, 1961) are common in solid-liquid mixing studies. In our flow-visualization studies, all the experiments were videotaped. Shots of various locations along the length of the vessel were taken. The video tapes were later run in slow motion to evaluate the mixing quality.

## Results and Discussion

In our studies, we observed that the downward-pumping impellers performed much better than upward-pumping impellers. As such, most of our experiments were performed with downward-pumping impellers. Within the range of solids concentration studied, we did not see any effect of the dispersed solid phase concentration on power draw for good mixing. In general, more power was required to draw down lighter solids than heavier buoyant solids.

We found that the key to homogenizing the buoyant solid particles or liquid droplets, was to create a controlled vortex by partially baffling the tank. Partial baffling produced mixing much superior to that obtainable with either full baffles or without baffles. With no baffles, all the solids were engulfed in a conical funnel, without any mixing. Full baffling completely failed to drawdown any solids at an aspect ratio of 2 or greater without the risk of burning the motor.

The optimum impeller position was when the impellers were placed halfway for each aspect ratio. For example, in a tank with an aspect ratio of 3, a three-stage mixer performed best with the lowest impeller placed at a clearance of $T/2$ away from the bottom plate, and the remaining impellers placed at a distance of $T$ away from each other (see Figure 1a).

The optimum diameter and blade-width for the PBTs was $T/2$ and $T/8$, respectively. The preferred baffle dimensions for the rectangular (partially immersed) baffles are: width = $T/10$ and thickness = $T/64$, and they should be placed at a clearance of $T/10$ from the wall. The clearance allowed easy access for the movement of the dispersed phase behind the baffles. This is quite important for plant scale operations involving larger tanks where clogging behind the baffles must be avoided.

Table 1 shows the effect of baffle-configuration on solid-liquid mixing in a tank of diameter of 0.203 m and an aspect ratio of 3 when three PBTs were placed in optimum locations (see above). The optimum configuration for partial baffling was attained by immersing three baffles *from the top* (placed at 3, 6 and 9 o'clock positions along the circumference of the tank) to varying depths inside the tank. In general, one or two baffles were dipped close to the top impeller blades and the third either halfway between the top impeller and the surface of the liquid or between the two top impellers (see Figure 1b).

For low aspect ratios, below 1.5, no distinction could be found between the performances of fully immersed narrow baffles and partially immersed rectangular baffles. However, for higher aspect ratios, partially immersed rectangular baffles performed better. This is shown in Table 2 for an aspect ratio of 3, when the tank was equipped with three PBTs placed in optimum locations.

The reason for preferring three baffles 90° apart (rather than 120°) was to create an off-centered vortex. This minimizes any tendency on a portion of the solids to adhere to the shaft, thereby reducing probable localized corrosion in larger industrial scale mixing.

In general, for an aspect ratio of 3, a three-stage, four-blade 45° PBT performed better than a 3-stage A100 marine propeller system. For example, when an 0.203 m diameter tank having an aspect ratio of 3 was equipped with A100 propellers, the

**Table 2. Comparison of Results in a Tank of $T = 0.203$ m and an Aspect Ratio of 3**

| (A) Power for Optimum Mixing with PBTs | | |
|---|---|---|
| Works | Description | Power, kW/m³ |
| This work | 3 Partially Immersed Rectangular Baffles | 0.105 |
| | 4 Fully Immersed $T/48$ Baffles | 0.280 |
| Hemrajani et al. (1988) | 4 Triangular Baffles | 0.220 |
| | 4 Full Length $T/50$ Baffles | 0.250 |
| **(B) Optimum Mixing Speed with Partial Baffles** | | |
| Works | Description | Agitator Speed, rpm |
| This work | 3 Partially Immersed Rectangular Baffles Using 3 PBTs | 300 |
| | 4 Fully Immersed $T/48$ Baffles Using 3 PBTs | 425 |
| | 3 Partially Immersed Rectangular Baffles Using 3 Propellers | 760 |
| Hemrajani et al. (1988) | 4 Full Length $T/50$ Baffles Using PBTs | 420* |

*Based on Eq. 3 with $n = 0.56$.

mixer had to be operated at a rpm of 760 to achieve a mixing quality equivalent to the same tank equipped with PBTs operated at 300 rpm. The fully-immersed $T/48$ baffles required 425 rpm for equivalent mixing quality (see Table 2b).

Following Rushton et al. (1950), we plotted $N_p N_{Fr}^{\beta}$ as a function of $N_{Re}$ in Figure 2 by fixing the parameters $\phi = 0.9$, $x = 0.1$-$1.0$ wt. %, and $S$ representing the optimum partial baffle condition (as described above) with a three-stage PBT system. For scale-up designs, we suggest that similar plots be made for the mixer and partial baffle assembly to serve as design guides for mixing of buoyant particles in a liquid. Equation 3 can be used to determine the required mixer speed in the commercial scaled-up vessel using a value of $n$ between 0.5 to 0.75 (in a partial baffle assembly, $n$ would depend upon the baffle configuration). One can then predict the power requirement in the scaled-up vessel by reading the value of $P$ from

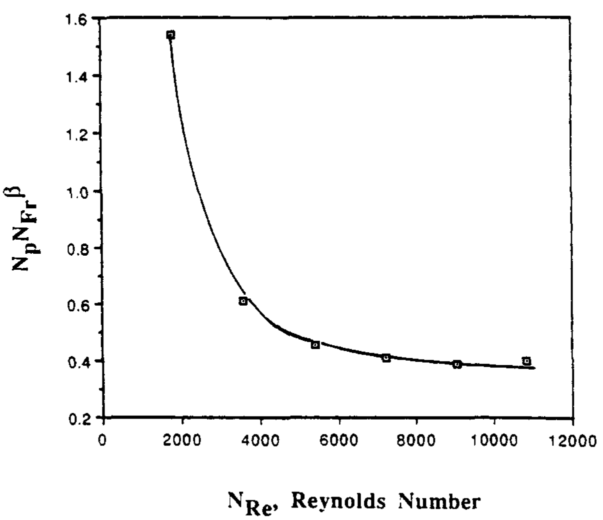


**Figure 2. Plot of $N_p N_{Fr}^{\beta}$ vs. $N_{Re}$ for a tank of aspect ratio of 3, equipped with 3 PBTs.**

the plot of $N_p N_{Fr}^{\beta}$ as a function of $N_{Re}$ obtained as a result of experiments in the proto-type vessel.

## Conclusion

The key to incorporating a buoyant phase into a carrier liquid phase is by controlling the vortex formation using partial baffles. The optimum diameter and blade-width for the PBTs are $T/2$ and $T/8$, respectively. The most optimum rectangular partial baffle configuration is obtained by immersing three baffles from the top (placed at 3, 6 and 9 o'clock positions) along the circumference of the tank to varying depths inside the tank (with at least one of the baffles placed close to the tip of the top impeller). For aspect ratios larger than 1.5, partially immersed rectangular baffles immersed to varying depths are more effective than fully immersed narrow baffles of widths $T/48$ or $T/50$. In general, a four-blade PBT system performs better than a 3-blade marine propeller system. Downward pumping PBTs are more effective in homogenizing the slurry than upward pumping PBTs.

A scale-up criterion is suggested on the basis of plotting the results of $N_p N_{Fr}^{\beta}$ as a function of $N_{Re}$ for fixed values of $\phi$, $x$ and $S$.

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## Notation

$a, b$ = constants used in Eq. 2
$D$ = diameter of agitator blade
$g$ = acceleration due to gravity
$n$ = exponent in Eq. 3
$N$ = agitator speed
$N_{Fr}$ = Froude number, $N^2D/g$
$N_p$ = power number, $P/(N^3D^5\rho_f)$
$N_{Re}$ = Reynolds number, $N^2D\rho_f/\mu_f$

$P$ = power to drive the motor
$S$ = shape factors
$T$ = tank diameter
$x$ = solids concentration, w/w %

### *Greek letters*

$\beta$ = defined as in Eq. 2
$\phi$ = ratio of particle to fluid density
$\mu_f$ = fluid viscosity
$\rho_f, \rho_p$ = fluid and particle densities, respectively

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