

DRAWDOWN OF FLOATING SOLIDS IN STIRRED TANKS

Oscar Khazam and Suzanne M Kresta

*Department of Chemical and Materials Engineering, University of Alberta,
Edmonton, Canada, T6G 2G6; email suzanne.kresta@ualberta.ca*

Abstract. Agitated tanks are used in several industrial processes to achieve complete draw down of floating solids in liquids. The design requirements for this process are limited to several initial studies in the literature, along with heuristics regarding the use of a surface vortex and the effect of solids wettability on the difficulty of mixing. In this study, the effect of the type of impeller, impeller submergence, and baffle configuration on the minimum draw down speed (N_{jd}) are reported. It is shown that the formation of a large surface vortex acts to hold particles in a compact layer close to the surface. Suppression of the surface vortex with baffles is recommended. In baffled tanks, solids drawdown is determined by the intensity of turbulence and mean circulation velocity of the liquid at the surface. The distribution of solids throughout the tank is strongly affected by the top to bottom circulation patterns. It is found that half baffles are very similar to full baffles in performance, but surface baffles offer several advantages: a significant reduction in N_{jd} and more robust performance at large submergences; a better distribution of solids; and a longer circulation time below the surface.

Key words: Floating solids, solid-liquid mixing, stirred tank, PBTU, PBTB, drawdown mechanisms.

1. INTRODUCTION

Particles may float on a liquid surface due to a low solid density, due to low solids wettability combined with a large contact area, or due to low bulk density of the solid powder. When a single particle is placed at the surface of a stationary denser and/or non-wetting liquid, as shown in Figure 1, the particle stays at the surface if the combined buoyancy and surface tension forces are greater than the gravitational force. Once the impeller is turned on and the fluid is in motion, two additional forces emerge in the system: the mean drag force and the dynamic forces due to turbulent velocity fluctuations and coherent meso-scale eddies. These forces and the gravitational force have to overcome the buoyancy and surface tension forces to draw the floating particles down from the surface, allowing them to be distributed throughout the tank. In this paper, the drawdown of floating solids is compared for a range of baffle geometries in order to determine the most efficient design strategy.

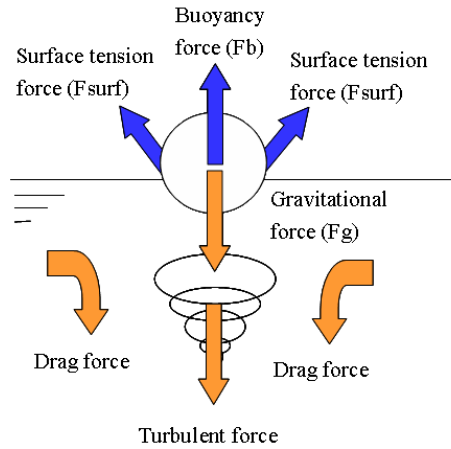


Figure 1: Forces that interact once a buoyant particle is placed at the surface of a denser liquid. Note that the drag force is determined by the axial component of the mean velocity.

Previous investigations [1-4] showed that substantial savings in power consumption can be achieved by choosing the proper impeller type and size. All authors conclude that radial flow impellers are not energy efficient for solids drawdown. They also report that mixed flow impellers achieve better results than purely axial impellers.

The underlying design objective associated with the drawdown of floating solids is to maximize contact between the solid and liquid phases for mass transfer and reaction. This problem can be divided into two parts: first, finding the best way to drawdown the floating particles from the surface, and second, distributing the particles evenly throughout the tank. In this paper, the first objective is quantified using N_{jd} , the just drawn down speed, and the second with CD , the cloud depth.

Three conventional baffle configurations (zero, one, and four full height baffles) and two possible novel configurations (four half-baffles, and four surface baffles) are evaluated. The half-baffles at the top of the tank were suggested as typical of some industrial installations, while the surface baffles were designed to have the minimum effective depth. These small baffles penetrate through the radial return flow in a typical circulation loop, eliminating the surface vortex while avoiding top to bottom circulation. The ideal configuration will provide low values of just drawn down speed, uniform distribution of particles, large values of sub-surface residence time, and will suppress air entrainment from the headspace. The just drawn down speed (N_{jd}), and cloud depth (CD) are measured directly, while the sub-surface residence time and air entrainment observations are more qualitative.

2. EXPERIMENTAL

Experiments were performed in a 0.24m diameter flat bottom transparent cylindrical tank. The liquid height was maintained constant ($H=T=0.24m$). The distance from the surface of the liquid to the centerline of the impeller (submergence, S) was varied from the impeller blade height to half of the total liquid depth ($0.01m < S < 0.12m$). Two impellers were used: a standard 45° pitched four-blade turbine (PBT) in up and down-pumping modes. Five baffle configurations were studied: zero, one, and four full height baffles, four half-baffles at the top, and four surface baffles of height $B_H=0.2T$. All of the baffles had the same dimensions: baffle width ($W=T/10$), and baffle thickness ($B_T=T/120$) and rose just above the surface.

Expandable polystyrene beads (EPS) with a specific gravity of 0.9 and tap water (998 kg/m³) were used for all the experiments. The EPS beads were prepared from unexpanded samples by holding them under hot water (70°C) until no particles remained on the bottom of the beaker. After expansion, the particles were sieved to separate them by size and their density was measured using a pycnometer. All of the particles are partially-wetting in water. For every series of experiments, the particles were weighed and gently dropped down the side of the tank with the impeller turned off. Next, a small impeller speed was set giving stagnant zones where a number of particles agglomerated at the surface. Then the speed of the impeller was gradually increased at intervals of 5 rpm until the stagnant zones of solids completely broke up and no solids remained at the liquid surface for more than 1 to 2 seconds. This speed was characterized as N_{jd} . It was difficult to determine N_{jd} exactly because even at higher impeller speeds some solid particles reappeared on the liquid surface. To minimize the error in N_{jd} , each value of N_{jd} was obtained from three different runs and averaged. The final results reported here are repeatable to ± 5 rpm.

The cloud depth (CD) is the perpendicular distance from the lowest point on the free surface of the liquid to the point where the concentration of particles drops dramatically. While N_{jd} gives the point where all of the particles leave the surface, and allows both design and motor sizing, the cloud depth gives an indication of how well the particles are dispersed throughout the tank. The cloud depth reported here is a subjective measure of the drop in concentration. For some configurations, the solids layer is very compressed and the CD measurement is straightforward. For other configurations, the concentration of solids changes in several stages, and the CD reported is the point beyond which very few particles penetrate. No direct measurement of concentration was available for this study. The CD was simply measured using a ruler, and averaged over three runs. The results are accurate to approximately 0.1T.

3. RESULTS

A previous publication by the authors [5] suggests that solids may be drawn down by three different mechanisms:

1. *Single vortex formation*: a large stable vortex forms in the center of the tank when no baffles are present. This vortex breaks up the stagnant zones at the surface, but does not distribute the solids throughout the tank. Instead, the solids are concentrated close to the surface of the vortex by centrifugal forces.
2. *Turbulent fluctuations*: this mechanism is characterized by a wavy and splashy surface with energetic surface eddies, particularly when small submergences are used. These eddies appear and vanish quickly, pulling solids down from the surface in small packets.
3. *Mean drag*: this mechanism is characterized by large swirls, waves, and strong circulation which sweep over the free surface, breaking up the stagnant zones intermittently and ingesting solids. The axial component of the mean velocity must be larger than the particle slip velocity at some point close to the liquid surface for this mechanism to be effective.

Combinations of these mechanisms can be found in most tank configurations, but one mechanism will generally dominate. The presence of baffles at the surface suppresses the single big vortex formation, allowing turbulent fluctuations and mean drag to dominate. When full or half baffles are used, there is strong top to bottom circulation, so particles are constantly being drawn down and quickly returned to the surface. When the baffling is

minimized to the case of surface baffles, a small precessing vortex appears close to the shaft. Particles are drawn down in this small vortex, and once they are below the baffles (20% of the tank depth), they swirl down toward the bottom of the tank in the tangential mean circulation. The tangential circulation gives a better distribution and seems to provide larger values of sub-surface residence time. Quantitative results are shown in Figures 2-5.

The just drawn down speed for the PBTB is shown in Figure 2. At very small submergences ($S/T < 0.15$), the drawdown is dominated by turbulent engulfment at the surface and N_{jd} is quite small. As the impeller descends below $0.4T$ for the full and half baffles, the dominant mechanism shifts to mean drag and N_{jd} increases rapidly. From $0.25 < S/T < 0.4$, both mechanisms appear to be active and N_{jd} is nearly constant. The rapid increase of N_{jd} beyond $S/T = 0.4$ for these two cases is due to changes in the intensity of the circulation loops and the turbulence at the surface. Once the distance between the impeller and the liquid surface exceeds $S/T = 0.3$, the wall jet which drives the up-flow in the recirculation loop disintegrates at $z/T = 0.7$ [6] so the mean flow and turbulence no longer penetrate to the surface. The just drawn down speed increases rapidly as a result. The half-baffle configuration does not significantly change N_{jd} relative to the fully baffled case. Four half-baffles are enough to create full top to bottom circulation loops which pull down the particles and quickly return them to the surface, similar to the four full baffles configuration.

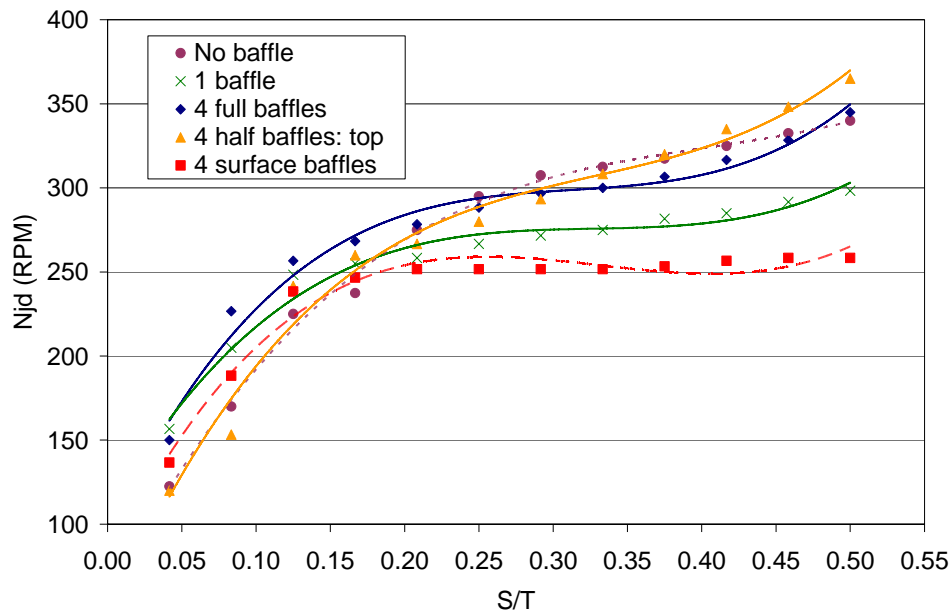


Figure 2: Effect of baffle configuration on N_{jd} for the PBTB ($D = T/2$, 2%v/v). The 4 surface baffles configuration performs better than the other two baffle configurations.

Surface baffles significantly reduce N_{jd} at large S/T for both the PBTB and the PBTU, as shown in Figures 2 and 3. By cutting off the bottom of the baffles, the drag in the middle and bottom zones of the tank is eliminated, forcing all of the dissipation and turbulence toward the surface. Even at big submergences, most of the energy dissipation is available for solids drawdown at the surface. This behavior makes it possible to place the impeller deeper in the tank without having to increase the speed to achieve drawdown of particles. One of the advantages of placing the impeller at a larger submergence is that air entrainment is reduced or eliminated. In most processes, prevention of air or vapour entrainment from the headspace

may be required to ensure the desired product quantity and quality [1]. Placing the impeller at larger values of S also results in larger values of cloud depth, as shown in Figures 4 and 5.

While the changes in N_{jd} with submergence for the PBTD are fairly smooth, the N_{jd} results for the PBTU given in

Figure 3 show a sudden transition which requires some explanation. N_{jd} increases rapidly from $S/T=0.32$ to $S/T=0.42$ in the fully baffled and half baffled configurations. At this submergence a secondary circulation loop forms and much of the energy from the impeller is diverted toward the bottom of the tank, requiring a sudden jump in N_{jd} to maintain solids draw down. The trend for the unbaffled configuration with the PBTU is similar to the PBTD, differing only in the maximum N_{jd} required at large submergences (350rpm vs 375 rpm).

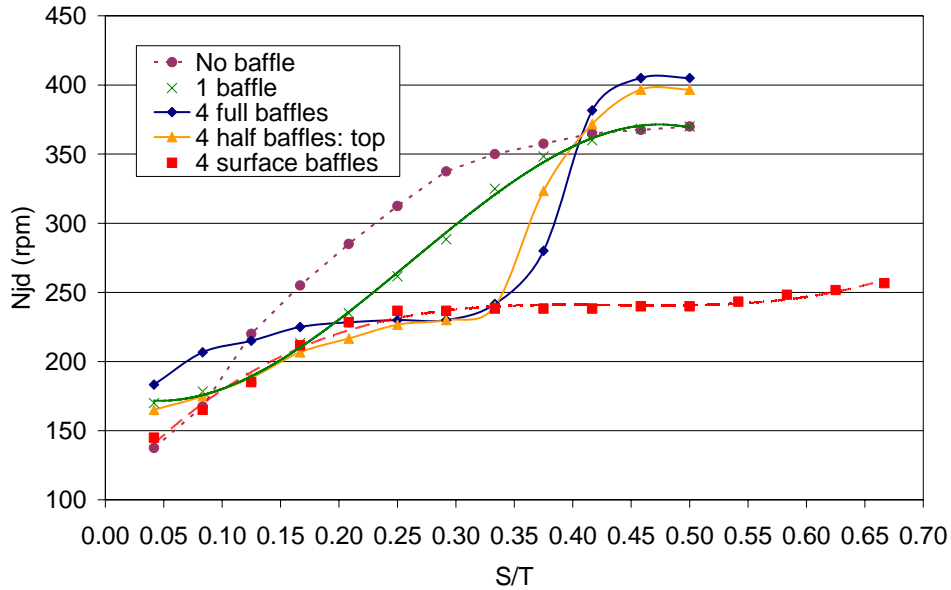


Figure 3: Effect of baffle configuration on N_{jd} for the PBTU ($D = T/2$, 2%v/v). The formation of a secondary circulation loop close to the surface produces a sudden increase in N_{jd} at $S/T \cong 0.35$ for the half-baffles and the full baffles. In contrast, the flow pattern for the surface baffles promotes the drawdown of the particles even for large values of S .

From the N_{jd} results, it is clear that there is very little effect of baffle configuration at small impeller submergences ($S/T < 0.15$), but for large submergences the surface baffles offer some significant advantages. For the PBTD, all baffles give smooth increases in N_{jd} as the impeller descends in the tank, but for the PBTU, there is a sudden jump in N_{jd} as the impeller drops below the point where a secondary circulation loop forms at the top of the tank – only in cases where there is strong top to bottom circulation driven by half or full height baffles. The second thing to consider is the quality of the suspension, or the distribution of solids in the tank, as given by the cloud depth.

The cloud depth is analogous to the cloud height for solids suspension, but is slightly complicated by the possibility of large deformations of the free surface. For the unbaffled configuration, the cloud depth was calculated by subtracting the vortex depth from the distance to the bottom of the particle layer when particles are added. Figures 4 and 5 show that the cloud depth for the unbaffled configuration gets smaller as S increases for both impellers. As S and N_{jd} increase the centrifugal forces on the particles due to mean flow will also increase, giving better particle separation, or more intense segregation of the phases.

Clearly, the performance of the unbaffled tank is significantly poorer than the other baffle configurations with respect to solids distribution.

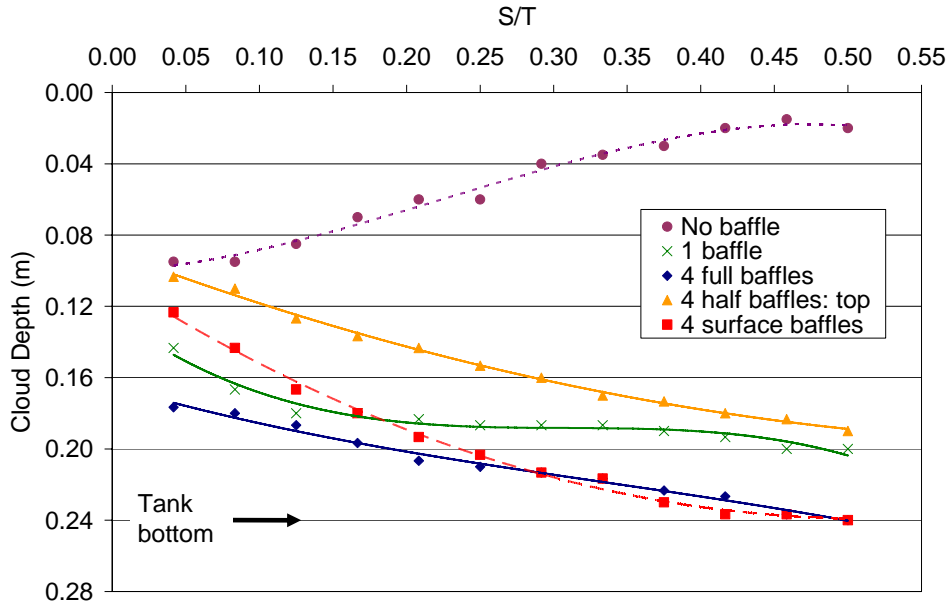


Figure 4: Cloud depth for the PBTB ($D = T/2$, $2\%v/v$) at N_{jd} . In the unbaffled configuration, particles are collected at the surface of the vortex due to centrifugal forces for both impellers.

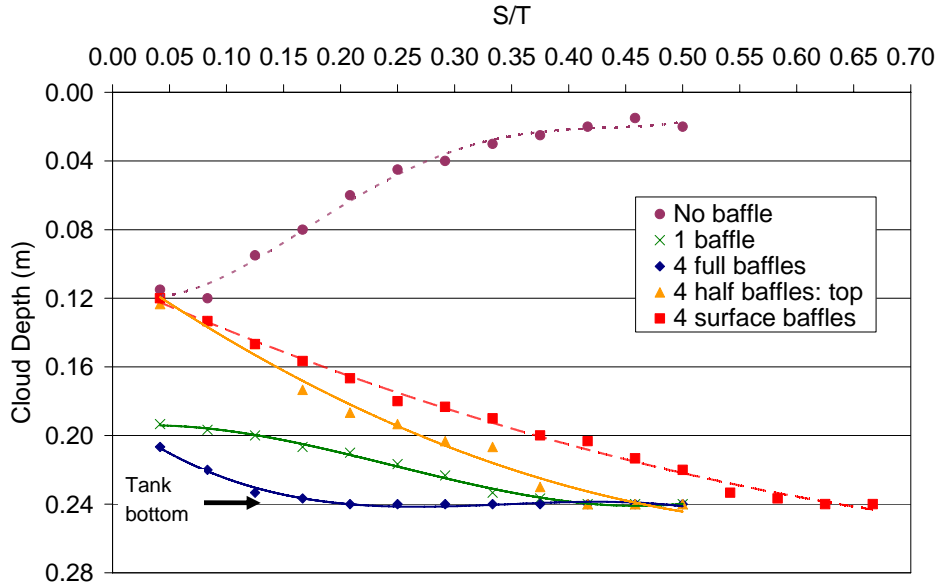


Figure 5: Cloud depth for the PBTU ($D = T/2$, $2\%v/v$) at N_{jd} . In the fully baffled configuration, the strong top to bottom circulation generated by this impeller drags the particles all the way to the bottom of the tank.

The results for the single baffle case and half baffles fall between those for the surface vortex and the fully baffled case, but are much closer to the fully baffled case. With a light solid like the expandable polystyrene beads, the concentration of particles is not uniform in

the tank even after large values of cloud depth are obtained. This non-uniformity for the single baffle case is not captured by the cloud depth results, because the surface vortex is unstable and the mean vortex depth could not be measured visually. On the other hand, the half-baffles circulation loop is weaker than for the four full baffles and so the cloud depth due to axial flow is much smaller.

In Figure 4 the values of cloud depth for both the fully baffled and the surface baffles configurations are similar for $S/T > 0.25$. However, the sub-surface residence time for the surface baffle configuration is higher than for the fully baffled configuration. The strong circulation loop associated with the full baffles brings the particles back to the surface almost immediately, while the tangential flow associated with the surface baffles keeps the particles below the surface much longer. For the PBTU, the unbaffled, one baffle and half-baffles configurations are a poor choice; the surface baffles offer better distribution and sub-surface residence time performance at large impeller submergences; and full baffles offer larger cloud depth at small impeller submergences.

Figure 5 shows the effect of submergence on cloud depth for the PBTU. For this impeller, complete dispersion of particles into the liquid phase is easily achieved all the way to the bottom of the tank for both the four baffle and one baffle configurations. The full baffles show a very rapid increase of CD all the way to the bottom of the tank for $S/T > 0.15$. Once again, the cloud depth for the surface baffles is smaller than for the four full baffles, and in fact the results for the surface baffles are very similar for the PBTU and the PBTU. In this configuration, the ability to place the impeller at larger submergences without increasing N_{jd} allows the surface baffles to achieve complete dispersion of solids at a lower N_{jd} than the four full baffles configuration at larger submergences. For $S/T = 0.50$, solids dispersion is essentially complete for both the full and surface baffles, but N_{jd} is 250 rpm for the surface baffles, and 400 rpm for the full baffles. During the experiments it was also observed that most of the ingested particles remain close to the surface in the upper circulation loop for the fully baffled configuration using the PBTU. It was difficult to identify a sudden drop in concentration for this configuration. With the surface baffles the distribution is more uniform and the drop in concentration is clearer. Baffle height strongly influences the flow patterns in the tank and has a large impact on the distribution of solids.

4. CONCLUSIONS

This study shows that surface baffles offer some advantages over other configurations for the drawdown of floating solids, giving lower values of N_{jd} , better solids distribution and sub-surface residence time, and finally allowing impeller placement deep in the tank to avoid air entrainment. The N_{jd} observed for the PBTU is more sensitive to both submergence and baffle configuration than the PBTU. A more extensive characterization of the surface baffles will offer a better understanding of the distribution of solids in the tank, and possibly suggest a wider range of applications of surface baffles for mixing processes.

5. ACKNOWLEDGEMENTS

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6. NOMENCLATURE

B_H	Baffle height (m)
B_T	Baffle thickness (m)
CD	Cloud depth (m)
d_p	Particle size (mm)

d_T	Impeller blade thickness (m)
D	Impeller diameter (m)
H	Liquid height in tank (m)
N_{jd}	Just drawdown impeller speed (rps or rpm)
P	Impeller power consumption (W)
Re_I	Impeller Reynolds number (-)
S	Submergence, distance from the surface to the centerline of the impeller (m)
T	Tank diameter (m)
v/v	Volume of particles / Total volume (-)
W	Baffle width (m)
w	Impeller blade width (m)
z	Vertical distance from the tank bottom (m)

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