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CLOUD HEIGHT IN SOLIDS SUSPENSION AGITATION

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The focus of this work is the experimental determination of cloud height (the height to which solids are suspended) in an agitated slurry as a function of the agitation intensity, solid physical properties, impeller type (pitched-blade or high efficiency), and system geometry. Cloud height is not strongly dependent on impeller type or solid physical properties, except for extremely rapidly-settling particles. However, it is dependent on the impeller diameter to tank diameter ratio (D/T), impeller off-bottom clearance to tank diameter ratio (C/T), and solids loading. The use of multiple impellers allows solids to be suspended to higher levels in tall batches. An intermediate impeller separation leads to optimal performance in terms of the power requirement to achieve a desired cloud height. Lower impeller separations do not yield significant performance improvements over a single impeller, while higher impeller separations lead to poor performance caused by "zoning" between the impellers.

Keywords: Cloud height; solids suspension; liquid–solid agitation

INTRODUCTION AND MOTIVATION

Because of its design importance, the vast majority of studies of liquid-solid agitation have focused on the just-suspended condition. However, for industrial agitator installations there is a need to understand the complete range of suspension levels. For instance, many storage tank applications require only that all of the solids remain in motion, not that they be suspended. Thus, to lower captial and operating costs, storage tanks are often designed at levels of agitation below the just-suspended condition. Conversely, applications such

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as catalytic reactors and overflow feed to centrifuges require that the solids be dispersed throughout the entire liquid volume.

Two important design parameters that are not often studied are the fillet volume and cloud height. These parameters characterize the amount of solid that remains unsuspended on the vessel base and the height to which the particles are suspended in the slurry, respectively. Together they represent a qualitative measure of suspension performance.

A more quantitative measure of suspension performance is the detailed distribution of solids throughout the system. Most phenomenological approaches to modeling the solids distribution in agitated slurries rely on the sedimentation-dispersion model, typically applied in a simplified, one-dimensional (axial) form. Both deterministic (Barresi and Baldi, 1987) and probabilistic (Kudrna *et al.*, 1980) formulations of this model have been used. However, the sedimentation-dispersion model has had only limited success and has not achieved widespread acceptance.

As computational power has increased, modeling of agitated slurries has been more closely linked to the system hydrodynamics. Recently, the network of zones model has been extended to liquid–solid systems (McKee *et al.*, 1994). Accurate modeling of concentration profiles in agitated slurries has been found to require detailed, three-dimensional models (Myers *et al.*, 1995). Although these computational models are promising, their very long current solution times make their use impractical for all but the most critical applications.

Lacking the detailed information of the complete solids distribution in an agitated slurry presents challenges for the design engineer. However, this detailed information is not always required for design, and cloud height often provides the necessary information for design purposes (Corpstein *et al.*, 1994). Previous work in this area has typically resulted in rules of thumb such as those presented by Shaw (1992) that state that the speed required for on-bottom solids motion is 0.69 times the just-suspended speed while the speed required for uniform solids dispersion is 1.46 times the just-suspended speed. This work focuses on a more quantitative characterization of the cloud height in liquid–solid agitation, including its dependence on solid physical properties, system geometry, and operating conditions.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus consisted of a 0.289 m diameter, cylindrical, flat-bottomed tank, and either pitched-blade turbines or high-efficiency impellers, the primary impeller styles currently used for solids suspension applications. The specific impellers studied were four-bladed, 45° pitched-blade turbines (referred to as P-4) or Chemineer high-efficiency impellers (HE-3). The HE-3 impellers were of standard design while the P-4 impellers had blade widths equal to twenty percent of the impeller diameter ($W/D = 0.20$).

The primary solid studied was an acrylic plastic. Its physical characteristics and those of the other solids studied are summarized in Table I. These materials were studied because they cover the spectrum of physical properties encountered industrially. For all but one experiment the solid was suspended in water. To study an extremely slowly settling material, the acrylic plastic was studied in salt water. The solids loading was usually 10 mass present (solids mass/slurry mass $=0.10$).

The typical experimental system geometry was as follows. The impeller off-bottom clearance of the lowest impeller or of a single impeller was twenty-five percent of the tank diameter ($C/T=0.25$), the impeller diameter to tank diameter ratio was thirty-five percent ($D/T=0.35$), and the liquid level to tank diameter ratio was equal to unity ($Z/T=1$). This system geometry was constant for all experiments except when it was desired to determine the effect that a specific geometric parameter had on the suspension performance. For these experiments, the new system geometry will be specified as needed.

For the dual-impeller experiments the liquid level to tank diameter ratio (Z/T) was 1.75 to accommodate large impeller separations. The solids loading was held at ten mass percent based upon a square batch geometry ($Z/T=1$; meaning that the mass of solids in the dual-impeller experiments was the same as in the single-impeller experiments). These experiments were performed with both HE-3 and P-4 impellers, with impeller diameter to

TABLE I Solid Physical Properties

Material	*Shape*	*Size* (μm)	*Density* (kg/m^3)	*Settling Velocity* (m/s)
Acrylic Plastic in Salt Water*	Rectangular Cylinders	2950	1179	0.00467
Ion Exchange Resin	Spheres	780	1053	0.0132
Acrylic Plastic	Rectangular Cylinders	2950	1179	0.0767
Sand	Granules	600	2590	0.0904
Coarse Sand	Granules	1850	2590	0.178

*The density of the salt water was 1160 kg/m^3. All other studies were performed in water.

tank diameter ratios of thirty-five and forty-eight percent ($D/T=0.35$ and 0.48). All of these experiments were performed with the acrylic solid, and the off-bottom clearance of the lower impeller was fixed at twenty-five percent of the vessel diameter ($C_1/T=0.25$). The separation between impellers was characterized in terms of the following dimensionless parameter.

$$S=(C_2-C_1)/D$$

For some experiments, it was necessary to determine the power draw. In these cases, the power number of the impeller system was determined using a calibrated reaction strain gauge. The just-suspended speed (N_{js}), cloud height (CH), and fillet volume, were measured by visual inspection and agreement of multiple observers. Replicate data was taken to ensure reliability and repeatability of the results. The cloud height and fillet volume fluctuate mildly with time, and the results presented here represent time-averaged values of these parameters.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 presents a sample of the data taken during this study (obtained with the HE-3 impeller, acrylic solid, $D/T=0.35$, $C/T=0.25$, $Z/T=1$ and $X=0.10$). At very low relative agitation speeds (N/N_{js} significantly less than one), the relative fillet volume is unity since none of the solids are suspended. As the speed is increased, some of the solid is suspended, and the relative fillet volume is slowly reduced. The relative fillet volume is dramatically reduced as the speed is increased from sixty to eighty percent of the just-suspended speed, with only about ten percent of the solids unsuspended when the speed is equal to eighty percent of the just-suspended speed. These conditions ($N/N_{js}=0.80$) roughly correspond to complete on-bottom motion of the solids (i.e., all solids move periodically even though they are not all suspended off the vessel base). This value of the relative speed is somewhat higher than the 0.69 found by Shaw (1992) to provide on-bottom solids motion. As the speed is further increased, the relative fillet volume slowly falls to zero at just-suspended conditions ($N/N_{js}=1$). This data indicates that substantial torque and power savings can be achieved if operation below just-suspended conditions is acceptable. At low relative agitation speeds when very few solids are suspended, the relative cloud height (CH/Z) is low. As the speed is increased and more solids are suspended, the relative cloud height slowly increases until the solids reach the liquid surface

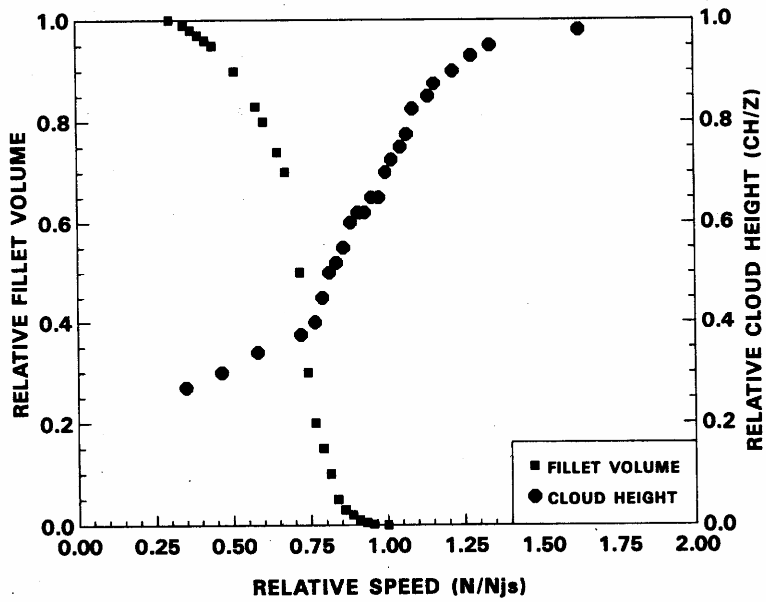

FIGURE 1 Typical fillet volume and cloud height data (obtained with the HE-3 impeller, acrylic solid, $D/T=0.35$, $C/T=0.25$, $Z/T=1$ and $X=0.10$).

($CH/Z=1$). Note that a relatively high speed, and corresponding high torque and power, are required to raise the cloud height to the liquid surface.

As mentioned previously, cloud height is only a qualitative measure of suspension performance, with a complete solids concentration field throughout the slurry providing a more detailed picture. Figure 2 presents a solids concentration profile measured in an agitated slurry at just-suspended conditions as part of a related study (Myers *et al.*, 1995; obtained with the HE-3 impeller and 200 micron diameter glass beads with a density of 2500 kg/m^3 and a terminal settling velocity in water of 0.0284 m/s; also $D/T=0.35$, $C/T=0.25$, $Z/T=1$, and $X=0.116$). This data indicates that throughout much of the slurry, the solids concentration is relatively constant, rapidly falling to zero near the cloud height location. Similar behavior is observed at other operating conditions, including as the cloud height approaches the liquid surface (not shown in a Fig.). Therefore, although the cloud height does not give the most detailed information possible, it does provide a sound qualitative basis for design. For more extensive information on solids concentration profiles, refer to the work of Myers *et al.* (1995).

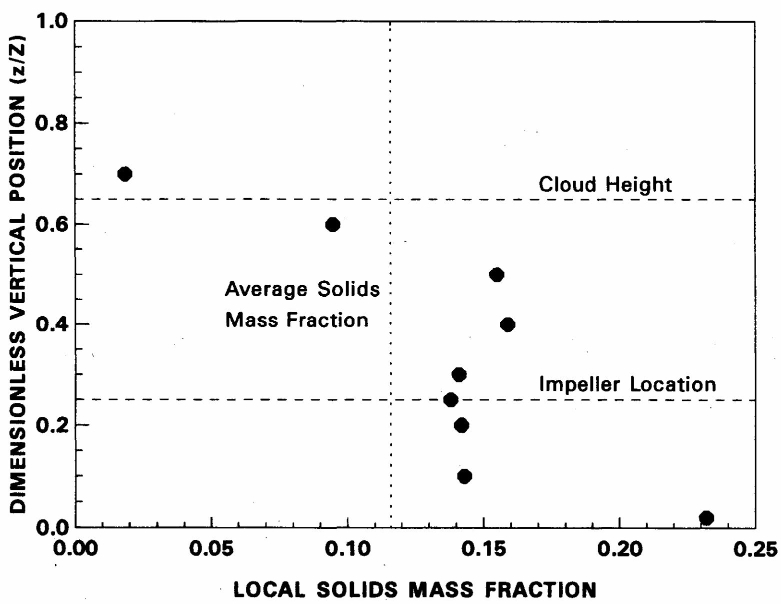

FIGURE 2 Typical solids concentration profile (reported by Myers *et al.* (1995); obtained with the HE-3 impeller, 200 micron diameter glass beads, $D/T = 0.35$, $C/T = 0.25$, $Z/T = 1$ and $X = 0.116$).

The influence of various parameters on the cloud height will now be described, first with single impellers, then with dual impeller systems.

Effect of Impeller Type

The cloud heights generated by the P-4 and HE-3 impellers with the acrylic solid are compared in Figure 3 (obtained with $D/T = 0.35$, $C/T = 0.25$, $Z/T = 1$, and $X = 0.10$). The data indicates that the behavior of the two impellers is essentially identical in this instance when plotted in terms of the relative speed of agitation (N/N_{js}; note that the P-4 and HE-3 impellers have different just-suspended speeds and each data set is normalized with respect to the just-suspended speed of the impeller of interest).

Effect of Physical Properties

The data of Figure 4 illustrates that, within a relatively narrow band, the cloud heights of the various solids are the same when plotted with respect

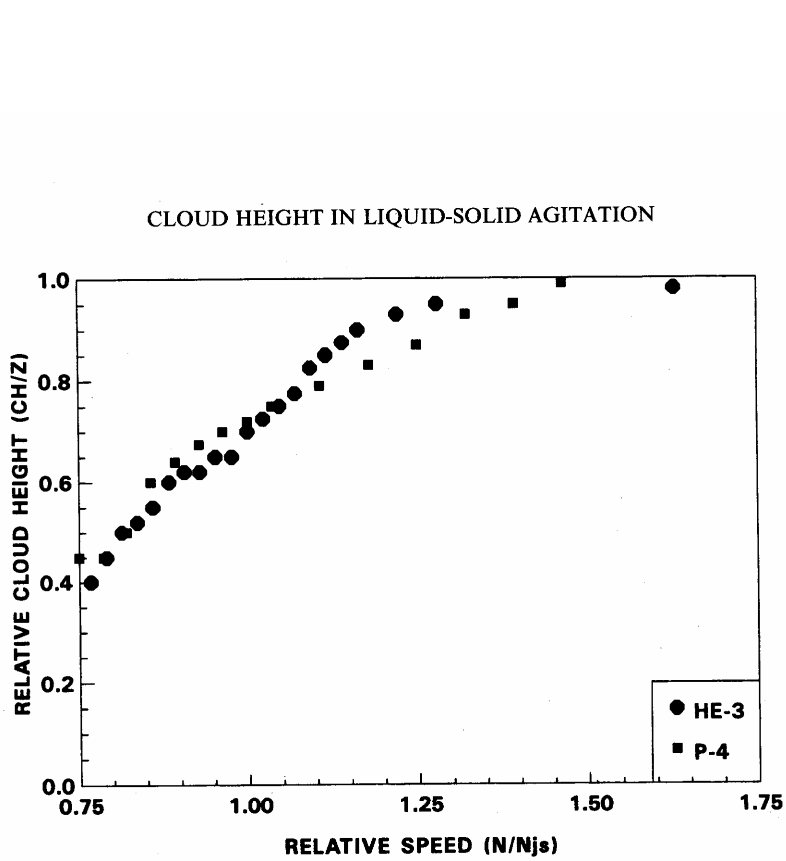

FIGURE 3 Comparison of the cloud heights produced by the P-4 and HE-3 impellers (obtained with acrylic solid, $D/T=0.35$, $C/T=0.25$, $Z/T=1$ and $X=0.10$).

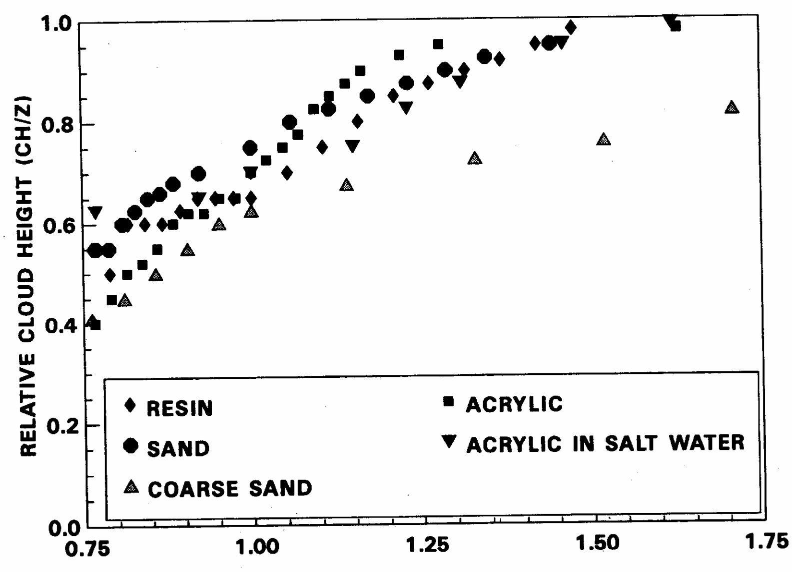

FIGURE 4 Comparison of the cloud heights produced by the HE-3 impeller with various solids (obtained with $D/T=0.35$, $C/T=0.25$, $Z/T=1$ and $X=0.10$; the properties of the solids are presented in Tab. I).

to the relative just-suspended speed (note that the different solids all require different just-suspended speeds and this data was taken with the HE-3 impeller with $D/T=0.35$, $C/T=0.25$, $Z/T=1$, and $X=0.10$; the properties of the solids are presented in Tab. I). Even the extremely slowly-settling solid (the acrylic plastic in salt water) does not have higher cloud heights than those observed with the more rapidly-settling solids. This result is in disagreement with the often stated conjecture that slowly-settling solids will be distributed throughout the entire vessel at the just-suspended speed (even Zwietering (1958) made this postulation in his pioneering solids suspension study). The one exception in the data of Figure 1 is the coarse sand that has an extremely high settling velocity. The cloud height of this material is significantly lower than those of the other solids.

Effect of Impeller Diameter to Tank Diameter Ratio (D/T)

Figure 5 demonstrates that the cloud height increases with increasing impeller diameter to tank diameter ratio (D/T) at just-suspended conditions and that the P-4 and HE-3 impellers exhibit similar behavior (the various impellers

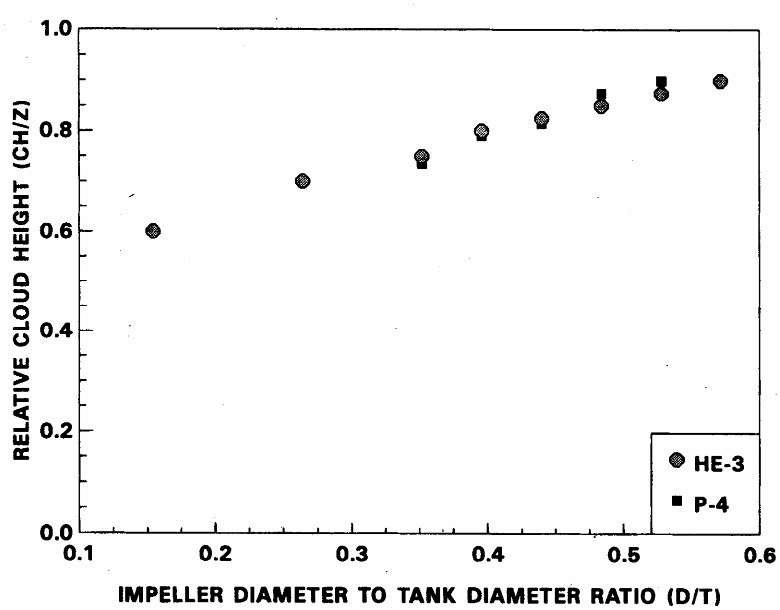

FIGURE 5 Cloud height dependence on the impeller diameter to tank diameter ratio (D/T) at just-suspended conditions (obtained with the acrylic solid, $C/T=0.25$, $Z/T=1$ and $X=0.10$).

were each operated at their individual just-suspended speeds; the data was obtained with the acrylic solid with $C/T = 0.25$, $Z/T = 1$, and $X = 0.10$).

The effect of impeller diameter to tank diameter ratio on the cloud height across the spectrum of relative speeds is shown in Figure 6 (obtained with the HE-3 impeller, acrylic solid, $C/T = 0.25$, $Z/T = 1$, and $X = 0.10$). Again, the cloud height increases with increasing impeller diameter to tank diameter ratio.

Figures 7 and 8 present this data in terms of the torque and power requirements needed to achieve a given cloud height (capital costs of an agitator can be directly related to the torque that the gear drive must transmit, while operating costs are directly related to power consumption). In these figures, torque and power are normalized with respect to the torque and power of a particular impeller (the HE-3 with $D/T = 0.35$ at just- suspended conditions). Figure 7 indicates that an impeller diameter to tank diameter ratio of forty-four percent ($D/T = 0.44$) yields the highest cloud height at all power levels; however, the differences between the larger impellers ($D/T = 0.35$, 0.44, and 0.53) are minimal at higher levels of agitation

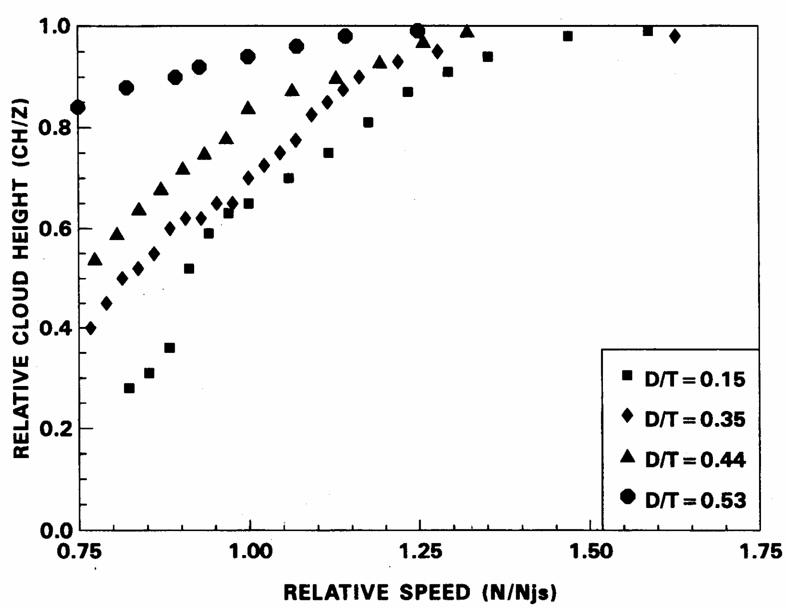

FIGURE 6 Cloud height dependence on agitation speed for various impeller diameter to tank diameter ratios (D/T) (obtained with the HE-3 impeller, acrylic solid, $C/T = 0.25$, $Z/T = 1$ and $X = 0.10$).

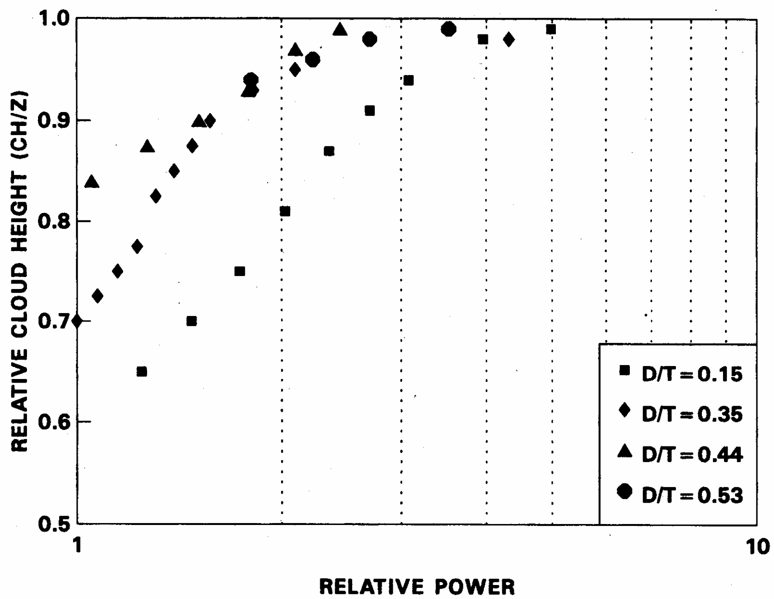

FIGURE 7 Power requirements to achieve given cloud heights for various impeller diameter to tank diameter ratios (D/T) (relative power is arbitrarily set to unity at just-suspended conditions with $D/T = 0.35$).

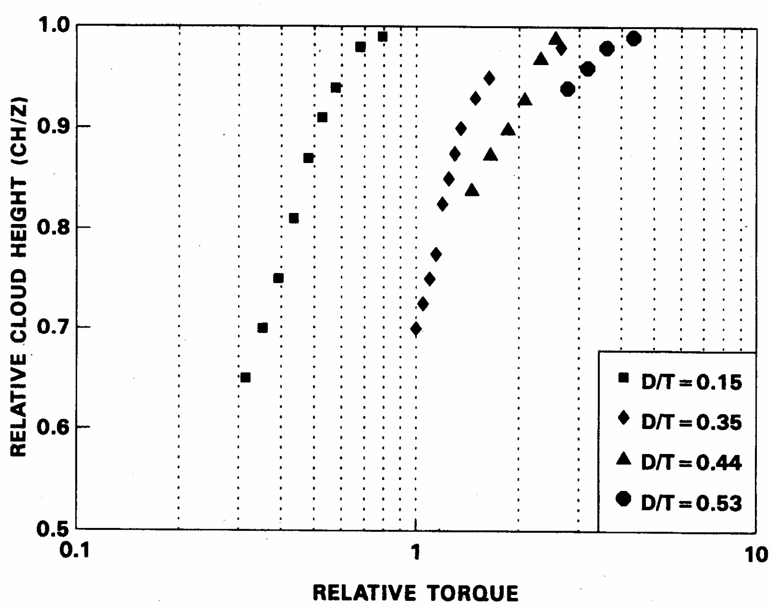

FIGURE 8 Torque requirements to achieve given cloud heights for various impeller diameter to tank diameter ratios (D/T) (relative torque is arbitrarily set to unity at just-suspended conditions with $D/T = 0.35$).

(relative powers greater than 1.5). Conversely, Figure 8 indicates that a given cloud height can be achieved with substantially lower torque requirements by using smaller impellers.

Effect of Impeller Off-Bottom Clearance to Tank Diameter Ratio (C/T)

The data of Figure 9 that demonstrates that the cloud height increases with increasing impeller off-bottom clearance may appear counter-intuitive (this data was taken with the HE-3 impeller, acrylic solid, $D/T=0.35$, $Z/T=1$ and $X=0.10$). In general, solids suspension performance is expected to improve as the impeller off-bottom clearance is reduced. In fact, the just-suspended speeds corresponding to the data in Figure 9 do decrease with decreasing impeller off-bottom clearance. The relative speed (N/N_{js}) of each data set of Figure 9 is normalized with respect to its own just-suspended speed, and when this data is compared in terms of torque or power requirements, there is very little difference in the cloud heights produced at different impeller off-bottom clearances.

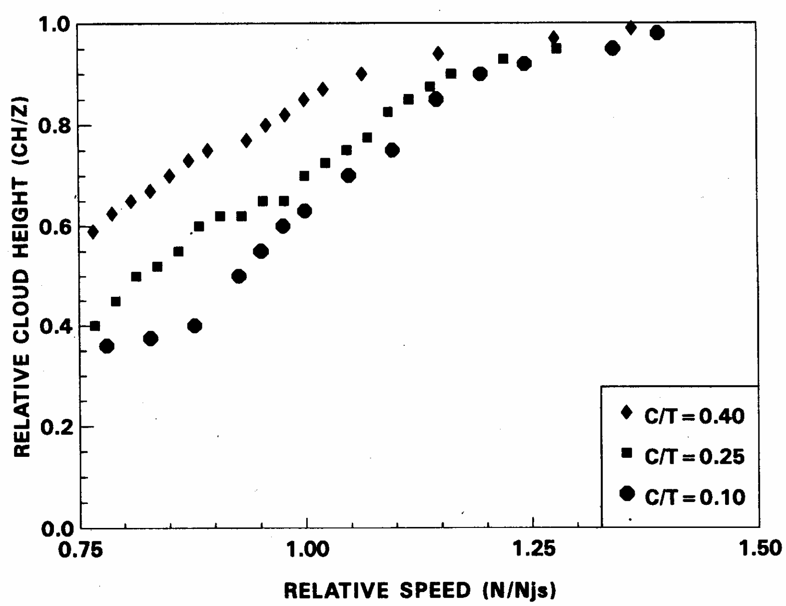

FIGURE 9 Cloud height dependence on impeller off-bottom clearance (obtained with the HE-3 impeller, acrylic solid, $D/T=0.35$, $Z/T=1$ and $X=0.10$).

Effect of Solids Loading (X)

As shown in Figure 10, solids loading influences the just-suspended cloud height (this data was taken with the HE-3 impeller, ion exchange resin, $D/T = 0.35$, $C/T = 0.25$, and $Z/T = 1$). At very low solids loadings, solids are distributed throughout most of the liquid volume (i.e., the just-suspended cloud heights approach the liquid surface (CH/Z is near unity)). The just-suspended cloud height then decreases with increasing solids loading, becoming essentially constant at the intermediate solids loadings of most practical interest ($0.10 \leqslant X \leqslant 0.40$). At very high solids loadings ($X > 0.40$) the just-suspended cloud height increases as the solids occupy a very substantial portion of the system volume. Note that although the results of Figure 10 were obtained with a slowly-settling solid, similar behavior has been observed for faster-settling materials.

Effect of Liquid Level to Tank Diameter Ratio (Z/T)

The preceding results were all obtained using square-batch geometry ($Z/T = 1$) . However, for industrial design purposes it is important to have an understanding of other geometries, particularly tall vessels in which the liquid level is greater than the vessel diameter ($Z/T > 1$). Figure 11 illustrates the dependence of the cloud height on the relative agitation speed and the impeller diameter to tank diameter ratio in a tall-batch geometry (this data was taken with the HE-3 impeller, acrylic solid, $C/T = 0.25$, $Z/T = 2$, and $X = 0.10$ for $Z/T = 1$). Note that in this instance the relative cloud height is normalized with respect to the vessel diameter rather than the liquid level (CH/T rather than CH/Z). These results indicate that it is very difficult to distribute solids throughout vessels that have liquid levels much greater than the vessel diameter when only a single impeller is used (this data was obtained with the HE-3 impeller, but similar behavior has also been observed with the P-4 impeller). In these instances multiple impellers should be used, and this subject will now be addressed.

Effect of Dual Impellers

For the systems studied here, the just-suspended speed was not influenced by the presence of a second impeller, indicating that the lowest impeller performed the majority of the work of suspension. Further, this means that if achieving just-suspended conditions is the sole design criterion, then the use of multiple impellers is not warranted since they will simply increase the

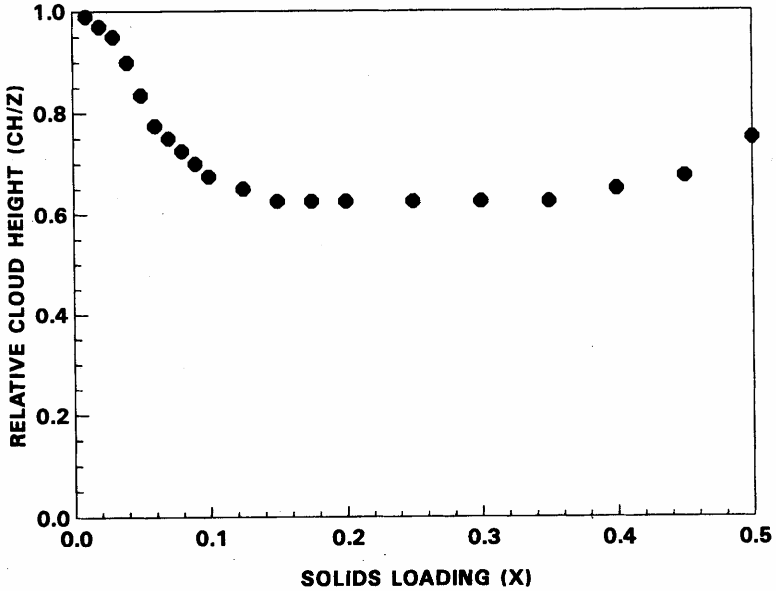

FIGURE 10 Just-suspended cloud height dependence on solids loading (obtained with the HE-3 impeller, ion exchange resin, $D/T = 0.35$, $C/T = 0.25$ and $Z/T = 1$).

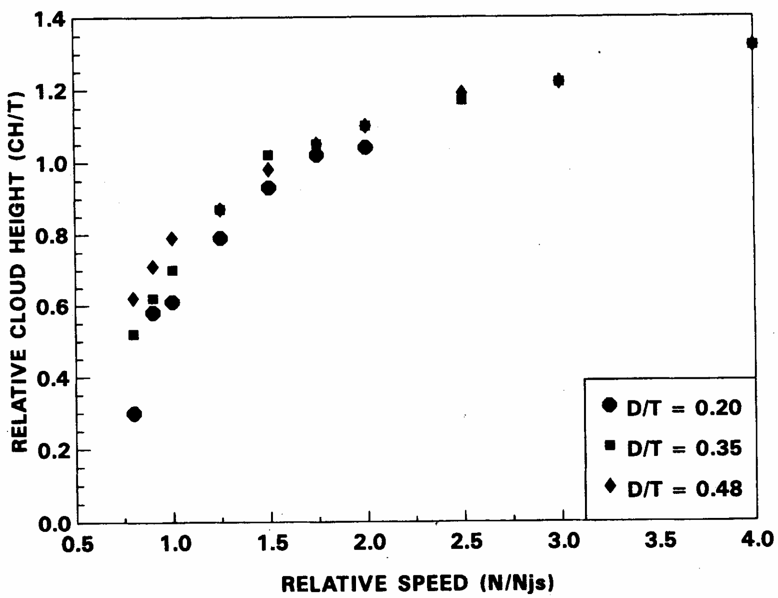

FIGURE 11 Maximum cloud height produced by a single impeller (obtained with the HE-3 impeller, acrylic solid, $C/T = 0.25$, $Z/T = 2$ and $X = 0.10$ for $Z/T = 1$).

torque and power requirements. However, if distribution of solids throughout the liquid is also a design consideration, then it remains to be seen if the use of multiple impellers is warranted.

Figure 12 demonstrates the effect of impeller separation on the HE-3 impeller cloud height for an impeller diameter to tank diameter ratio of thirty-five percent ($D/T=0.35$; also, this data was obtained with the acrylic solid, $C_1/T=0.25$, $Z/T=1.75$ and $X=0.10$ for $Z/T=1$). The data indicates that the suspension performance is best for an impeller separation equal to three impeller diameters ($S=3$). Although not shown in the figure, data taken at an impeller separation equal to three and one-half impeller diameters ($S=3.5$) indicates that "zoning" occurs. Under these conditions, only a small amount of the discharge flow from the upper impeller reaches the inlet flow of the lower impeller. Because of this limited interaction between the flows generated by the two impellers, there is a distinct decrease in solids concentration above the lower impeller. At an impeller separation equal to four impeller diameters ($S=4$), there is no interaction between the flows generated by the two impellers, and the upper impeller exerts almost no influence on the cloud height. In this instance very few solid particles are lifted higher than they would be if only a single impeller was used.

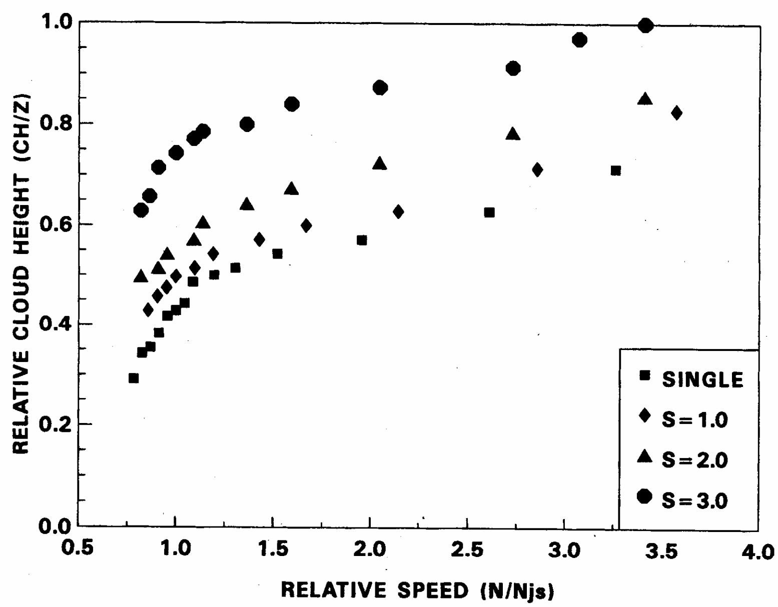

FIGURE 12 Impeller separation influence on the cloud heights produced by a dual HE-3 impeller system (obtained with acrylic solid, $D/T=0.35$, $C_1/T=0.25$, $Z/T=1.75$ and $X=0.10$ for $Z/T=1$).

Figure 13 is the same data except that the cloud height to liquid level ratio is plotted as a function of power input. The power has been normalized relative to the power consumption of the single impeller at the just-suspended speed. This figure indicates that the optimum suspension performance occurs at an impeller separation of three impeller diameters ($S=3$) for any power; that is, for a given power consumption the cloud height to liquid level ratio is the highest for an impeller separation of three impeller diameters.

Figure 14 illustrates the effect of dual impeller separation on the pitched-blade turbine suspension performance for an impeller diameter to tank diameter ratio of thirty-five percent ($D/T=0.35$; also, this data was obtained with the acrylic solid, $C_1/T=0.25$, $Z/T=1.75$ and $X=0.10$ for $Z/T=1$). The data indicates that for the most part, an impeller separation of two impeller diameters ($S=2$) offers the best performance. An impeller separation of three impeller diameters ($S=3$) does exhibit higher cloud heights, but only for high relative agitation speeds (N/N_{js} greater than about 1.5). Figure 15 is the same data except the suspension performance is plotted as a function of normalized power as defined previously. From this plot, the failure of the high impeller spacing ($S=3$) at low power

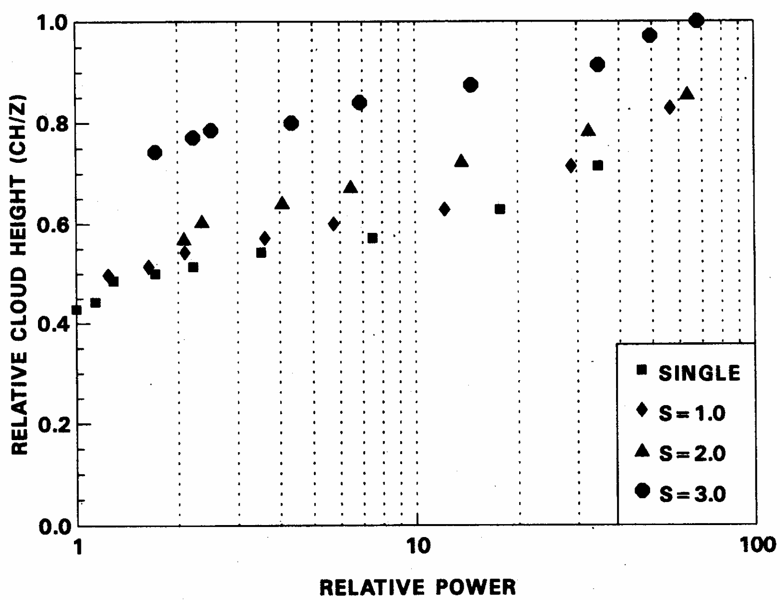

FIGURE 13 Power requirements to achieve given cloud heights for the dual HE-3 impeller system (relative power is arbitrarily set to unity at just-suspended conditions with the single impeller).

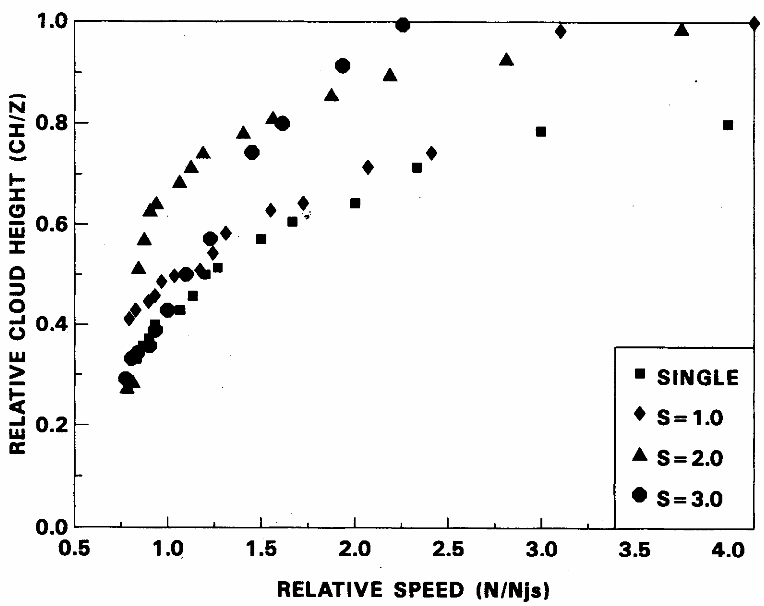

FIGURE 14 Impeller separation influence on the cloud heights produced by a dual P-4 impeller system (obtained with acrylic acid, $D/T=0.35$, $C_1/T=0.25$, $Z/T=1.75$ and $X=0.10$ for $Z/T=1$).

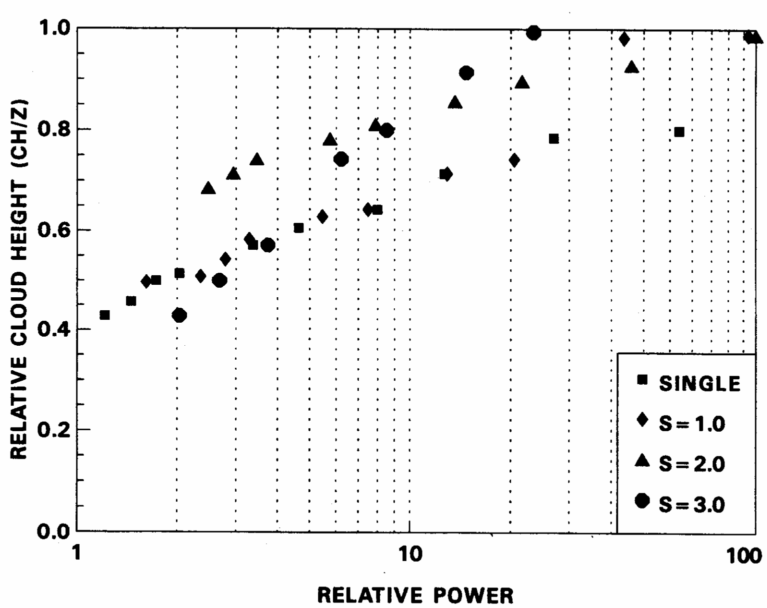

FIGURE 15 Power requirements to achieve given cloud heights for the dual P-4 impeller system (relative power is arbitrarily set to unity at just-suspended conditions with the single impeller).

inputs is even more evident. It is not until the relative power is equal to approximately 6 that it outperforms the other configurations.

At an impeller diameter to tank diameter ratio of forty-eight percent ($D/T = 0.48$), a separation of two impeller diameters ($S = 2$) was found to be optimal for the HE-3 impeller while a separation of one impeller diameter ($S = 1$) was found to be optimal for the P-4 impeller. However, for both impellers, larger separations could be used at high power inputs. The ability of the HE-3 impeller to perform adequately at larger impeller separations than the P-4 turbine is due to the highly-axial discharge flow of this impeller. The P-4 turbine discharge flow has a larger radial velocity component which causes zoning between the impellers to occur at lower separations.

SUMMARY

The effects of physical properties, system geometry and operating conditions on the cloud height in solid suspension agitation have been characterized. The data indicates that impeller type and physical properties do not strongly influence cloud height when the data is interpreted in terms of the relative speed (N/N_{js}) except for the fastest-settling solids studied. However, impeller diameter to tank diameter ratio (D/T), impeller off-bottom clearance to tank diameter ratio (C/T), and solids loading do affect the cloud height. For the HE-3 impeller, an impeller diameter to tank diameter ratio of forty-four percent ($D/T = 0.44$) was found to be optimal in terms of the power requirements to yield a specified cloud height. The torque requirements of the HE-3 impeller to produce a specified cloud height were found to be minimized by using small impeller diameter to tank diameter ratios.

Distribution of solids in tall vessels ($Z/T > 1$) was shown to be difficult with a single impeller, and it was seen that the use of multiple impellers in these systems is justified. Optimal impeller separation depended on the impeller type and impeller diameter to tank diameter ratio. The HE-3 impeller was found to be capable of being used at larger separations than the P-4 impeller, and both impellers required reduced impeller separations at larger impeller diameter to tank diameter ratios.

Given the potential value of the cloud height information presented here, additional work in this area should be pursued. In particular, the influence of draft tubes on cloud height should be determined. Draft tubes are often used in tall vessels to promote distribution of the solids throughout the vessel. A second area is the statistical quantification of the effects of variable interactions on cloud height. The primary variables to consider are the impeller type, off-bottom clearance, diameter, and separation in multiple impeller systems. Kresta and Wood (1993) and Myers *et al.* (1996) have demonstrated that interaction between these variables can significantly alter the flow pattern in an agitated vessel.

Acknowledgements

The assistance of Julian B. Fasano and Robert R. Corpstein of Chemineer, Inc. is gratefully acknowledged.

NOTATION

- C Impeller off-bottom clearance (measured from the vessel base to the lowest point on the impeller), m
- CH Cloud height, m
- D Impeller diameter, m
- N Agitation speed, s^{-1} (revolutions per second)
- N_{js} Just-suspended speed, s^{-1} (revolutions per second)
- S Impeller separation $((C_2 - C_1)/D)$, dimensionless
- T Vessel diameter, m
- W Impeller blade width, m
- X Solids loading (solid mass/slurry mass), dimensionless
- z Vertical distance from the vessel base, m
- Z Slurry height, m

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