Mixing Quality Characterization in Separation Process Tanks Part 2 Solids - Suspension (U)

by

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**Mixing Quality Characterization in Separations Process Tanks
Part II: Solids-Suspension (U)**

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July 31, 1995

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SUMMARY

An experimental study was performed to document the quality of mixing for dilute solids suspension in an aqueous phase in baffled, paddle-agitated, cylindrical tanks used in Separations canyon facilities. Experimental measurements were provided for those variables that are capable of adjustments in the full scale: namely impeller speed, height of the total liquid, and number of impellers on the shaft. Appropriate total liquid levels and minimum impeller speed for just complete suspension of solids were established for the full scale operation. The effects of particle size distribution and mean concentration of solids are demonstrated, and conditions under which the regular single sampling point gives results comparable to the average of variously placed measurements around the vessel are identified. Solids distribution in the radial and axial directions were examined and some recurring trends have been identified.

Minimum impeller speed for just complete suspension in the small scale tank was achieved at 370 rpm. Scale-up relationships based on the conservative equal power per unit volume of agitated mixture on two geometrically similar scales of operation suggested a 1.7-fold increase of the plant impeller speed to at least 120 rpm for the attainable condition of just complete, but non-uniform, suspension of solids. The axial and radial distribution of solids in the agitated liquid show an overall decrease of solids concentration with elevation above tank floor; a small, but distinct, increase in concentration just above each impeller was observed. The mean concentration gradient in the radial direction was found steadily decreasing with increasing impeller speed and the number of impellers submerged.

A simplified mass balance and coil impediment calculations indicate the need for new sampling techniques to explore the region around and between the impellers. Such sampling techniques will help to avoid dangerously high excessive solids concentrating in the region between the inner coil helix and impeller shaft when the density difference between the solids and the liquid are high.

INFORMATION ONLY

INTRODUCTION

Nuclear criticality safety in Separations canyon facilities is maintained primarily by control of the concentration of fissile materials in process equipment. The avoidance of criticality safety hazards in large process vessels may depend upon the accumulation of solid fissile materials in a given part of the process not exceeding a certain low specified critical mass limit. Confidence in the attainment of this goal is clearly dependent upon how a measurement of solids concentration from the local sampling technique relates to concentrations elsewhere in the vessel, and on the quality of mixing prevailing under operating conditions. Clarification was therefore needed of the relationship between the local concentration of solids found at the present regular sampling point, and the prevailing maximum and average throughout the vessel.

The suspension of solid (dispersed) phase in an agitated liquid phase involves a number of distinct stages, each of which can be reasonably well defined. In stage 1, the solid particles on the vessel floor are undisturbed due to the flow induced by the low-speed impeller being insufficient to cause any suspension. In stage 2, the solid particles are either lifted up or set in motion on the vessel floor due to an increase in the impeller speed. The rate of solids suspension increases with impeller speed until a minimum speed for just complete suspension, N_m , is achieved. At speeds higher than N_m , no further solids can be put into suspension but the overall suspension becomes more homogeneous as described by Buurman et al¹ and Musil². Gross homogeneity in which the local solids concentration in the tank is the same throughout the aqueous phase is approached in stage 4. In contrast to the work of Buurman et al¹, which never achieved gross homogeneity of the solid suspension, Magelli et al³ reported absolute homogeneity throughout their vessel in their study on suspension of polystyrene particles in water, where the density difference was only 0.02. Evidently the density difference between the phases is a major factor in the approach to grossly uniform suspensions.

In Separations canyon tanks, the suspension of solids in the aqueous phase is achieved by shear-type, radial flow, paddle agitators (flat-blade turbines) which are known to be more effective for liquid-liquid dispersion. Presently, there are no data or documentation available on the quality of mixing provided by these agitators for suspension of solids. Similarly, the adequacy of the local sampling technique to provide representative samples in the canyon process tanks known to contain solid fissile materials has yet to be

determined. The objective of this experimental study was to provide sufficient data that would characterize the quality of mixing for solids suspension for two geometrically similar scales of operation. This would involve those variables that are capable of adjustment on the full scale: namely agitator speed (N), height of total liquid in the vessel (H), number of agitators (n) on the shaft, mean concentration of solids ($\bar{\phi}$), and particle size distribution. Since the rate of mixing was not critical for this work, the main focus was to determine the distribution of solids both in the radial and axial directions as determined from variously spaced measurements throughout the tank.

EXPERIMENTAL

Materials and Equipment

The materials used in this study were tap water and commercial grade sea sand (Lot # 950067) obtained from Fisher Chemical, Fair Lawn, New Jersey. The sand had a particle density of 2.65 kg/m^3 and a broad particle size distribution. The screen analysis of the commercial sand is listed in Table 1. The mean solid concentration for the majority of test runs was 1 wt % unless otherwise specified.

A schematic diagram of the experimental equipment is shown in Figure 1. The equipment consisted of a cylindrical, flat-bottomed, Plexiglas tank with an inside diameter of 18 inches and overall height of 36 inches. For solids suspension, Lyons⁴ suggested that the smallest vessel should be at least 12 inches in diameter and the impeller should be no less than 4 inches in diameter. Hixson and Wilkens⁵ stated that an 18-inch diameter is the smallest size tank which may be used to obtain results reproducible in the full scale. The small scale tank used in the present work was equipped with six radial baffles of width equal to 1.25 inches. Three nested coil helix made of 0.5-inch diameter stainless steel tubing was fitted inside the baffles. Agitation in the tank was provided by two shear-type, radial flow, paddle agitators, each of which was equipped with four flat blades mounted on a centrally located shaft. The blades had a diameter of 4.5 inches and a width of 1 inch. The impeller blades of the two agitators were spaced 9 inches apart.

The paddle agitators were driven by a 1.8 HP air motor supplied by Gast Manufacturing Corporation, Benton Harbor, Michigan. The air motor was connected to a 20-pound in-house compressed air through a pressure regulator obtained from ARO Corporation, Bryan, Ohio; the regulator was equipped with a pressure gauge and a filter. A

lubricator was connected in-line as close as practical to the air motor. All sizes of equipment were scaled down approximately by a factor of 1:5 to maintain geometric similarity with the full scale (8 feet diameter x 11 feet high) Separations canyon tanks. Dimensions of the small and full scale equipment are listed in Table 2.

Sampling Technique

Different techniques are used for sampling agitated tanks. Many of them are visual observation techniques which may not be appropriate for in-plant operations. Thus grab sampling and light transmittance devices are used in situations when visual observation techniques are not practical. In the grab sample technique, a sample of the suspended solid is physically withdrawn and then filtered, dried, and weighed. Although this procedure is tedious, it has been successfully used to study the suspension of solid particles in agitated tanks and the effect of operating variables.

In the present study, samples of suspended solids were taken from variously spaced locations in the tank using a grab sample device similar to that employed by Hixon and Tenney⁶, Miller and Mann⁷, and Skelland and Lee⁸. This device, which is schematically shown in Figure 2, consists of a stainless steel tube, 11 mm inside diameter and 95 cm (37.5 inches) long, fitted with a 3 mm diameter extension rod. The rod was connected to a 13 mm diameter stainless steel plug at the lower end and a 19 mm diameter knob at the upper end. A 2 mm diameter stainless steel spring (expansion type) was enclosed between the upper ends of the tube and the extension rod. The plug was perfectly seated on the lower end of the tube when the spring was fully extended and, when it is forced down and quickly released, a sample was trapped inside the tube. A removable ring was attached on the outside of the sample tube to allow up and down movement of the sampler within the tank. No leakage of the tube was encountered.

Procedure

Experimental runs were performed by varying the impeller speed (N) and the total liquid height (H) while maintaining the mean concentration of solids constant at 1 wt %. The aqueous phase (tap water) was charged to the tank and the liquid depth was adjusted to the desired level using a graduated scale on the transparent tank wall. A known amount of the solid (sea sand) was added to the tank to bring the mean solid concentration to 1 wt %. The solid-liquid system was agitated at different impeller speeds and a hand-held

phototachometer was used to measure instantaneously the impeller speed. After turbulent agitation was fully established, which usually occurred in less than 5 minutes, the tank was sampled from multiple sampling locations both in the axial and radial directions using the grab sampling device described earlier. At each sampling location, the grab sampler was quickly inserted in the tank and, after 10 to 15 seconds during which the disturbances caused by the tube insertion was allowed to disappear, a sample was trapped. The sampler was then quickly removed from the tank, wiped clean, and the sample transferred to a beaker. The liquid was carefully drained and the volume of the liquid was measured; the solids were oven-dried and carefully weighed. The local wt % of solids was calculated from the weight of the sand and the volume of the sample. Prior to starting a new run, the tank was emptied and fresh tap water and sea sand were charged in the correct proportions to bring the concentration of solids to 1 wt %.

The experimental test runs were performed without a Task and QA plan. However, important experimental controls were applied. First, the total height of liquid was carefully measured. The aqueous phase was added to the tank and the level was carefully measured using a ruler and the graduation scale on the transparent tank wall. The liquid level readings were taken by more than one observer to minimize possible observer bias. A known amount of solids (sea sand) was added to the tank to bring the mean concentration of solids to 1 wt%. Because the amount of solids charged to the tank was so small, the total liquid height did not change and the error in the level reading remained the same at the precision of the ruler and graduation scale on the tank wall. Thus the transparent tank wall, graduation scale, and careful observation by more than one observer were sufficient controls and the procedure would have been no different had these test runs been performed under a Task and QA plan.

The phototachometer for measuring the impeller speed was calibrated directly in revolutions per minute using a manufacturer's standard calibration technique. The tachometer was calibrated directly in revolutions per minute using a fluorescent light bulb which provides a reading of 7200. Because the manufacturer's procedure would have been used had the test runs been conducted under a Task and QA plan, the controls employed was adequate and meet QA requirements.

RESULTS

The measured local weight % solids were obtained from variously spaced sampling points in the agitated tank as a function of impeller speed (N). The data are presented in Appendix A, Tables A-1, A-2, and A-3 for different total liquid height (H), mean solid concentration ($\bar{\phi}$) and Particle size distribution (PSD), respectively. These data were employed to compute the local mixing quality (η) at the regular single sampling point (denoted by η_{reg}) and the average of η values obtained from variously placed measurements around the vessel (denoted by η_{ave}) at given levels of H and N . The mixing quality (η) was defined as one minus the absolute fractional deviation of local solids concentration from the mean solid concentration (i.e., $1 - \Delta\phi/\bar{\phi}$, where $\Delta\phi$ is $\text{abs}(\bar{\phi} - \phi)$).

Figures 3 and 4 show plots of mixing quality as a function of the impeller speed when a single impeller is submerged and Figures 5 and 6 show the plots when both impellers are submerged. Figure 7 shows the ratio of the local mixing quality to the average in the tank (η_{reg}/η_{ave}) as a function of the impeller speed when lower impeller is submerged and Figure 8 represents when both impellers are submerged.

The concentration of solids in the tank was measured half-way between the following radial locations: ($R - r_{oc}$), ($r_{oc} - r_{mc}$), and ($r_{mc} - r_{ic}$) corresponding to between the tank wall and the outer coil helix, between the outer coil helix and middle coil helix, and between the middle coil helix and the inner coil helix, respectively. The region between the inner coil helix and the impeller shaft was inaccessible to sampling device. At each radial location, measurements were obtained at different axial positions (h) above the vessel floor. The mean value of the solid concentration in the above mentioned radial locations was referred to as the mean radial concentration (denoted by $\bar{\phi}_r$). The values of $\bar{\phi}_r$ are plotted in Figures 9 to 11 as a function of the impeller speed (N) for the total liquid heights H5, H6 and H7, respectively.

Figure 12 shows the plots for the mixing quality average (η_{ave}) as a function of the impeller speed for different particle size distributions. The following narrow particle sizes were selected for this study: 150-180 μm , 180-300 μm , 300-425 μm , and 526-600 μm . For each particle size distribution, the impeller speed was varied in the range from 100 to 528 rpm, and samples of the suspended solids were obtained from variously spaced sampling points in the tank. Figure 13 shows the mixing quality average (η_{ave}) as a function of impeller speed for various mean concentrations of the solid in the tank. The data

in Figure 13 were obtained using a wide range of particle sizes (i.e., 45 - 600 μm). Typical plots of the solid concentration as a function of the axial position (h) above the vessel floor are shown in Figures 14 through 16 corresponding to the submergence of one impeller only, and in Figures 17 through 20 representing when both impellers are submerged.

DISCUSSION

Minimum impeller speed for just suspension and acceptable total Liquid Levels

The minimum impeller speed for just complete suspension of solids was determined both from visual observation of the movement of solid particles on the illuminated tank bottom through an inclined mirror and analyses of measured local solids concentration for the prevailing experimental conditions. The visual techniques were adopted by Zwietering⁹ and Nienow¹⁰ while the methods using experimental data to determine the minimum impeller speed for just complete suspension, N_m , were used by Shamlou and Koutsakos¹¹, Bourne and Sharma¹², and Piero et al¹³. In the visual techniques, N_m was supposedly achieved when none of the solid particles remain stationary on the base for more than 1 to 2 seconds.

In the present study, N_m was determined from the mixing quality data at the regular sampling location as a function of the impeller speed. The plots shown in Figure 3 exhibit a maximum or a peak at 370 rpm, corresponding to the minimum impeller speed for just complete suspension of solids in the tank for the case when only one impeller is submerged (i.e., $H = H1$ to $H4$). The minimum speed, 370 rpm, places the operation in dispersed stage 3 first shown schematically by Hassan¹⁴ for liquid-liquid systems. Figure 5 shows that, when both impellers are submerged in the agitated liquid (i.e., $H = H5$ to $H8$), the minimum impeller speed for just complete suspension is also attained at 370 rpm. Figures 4 and 6 reinforce the findings that N_m was always achieved at 370 rpm for the prevailing conditions in the tank. The minimum speed for just complete suspension for the plant scale is about 120 rpm based on conservative equal power per unit volume scale-up correlation. Thus the current plant impeller speed (68 rpm) is insufficient to just completely suspend the solids in canyon tanks and, therefore, should be increased roughly 1.7-fold to at least 120 rpm. Since the minimum speed for liquid-liquid dispersion in stage 3 was previously achieved at 173 rpm, this speed should ensure that both solids suspension and liquid-liquid dispersion could be attained in the canyon tanks. However, a 30% increase to 225 rpm

would give axially more uniform distribution for both solids suspension and liquid-dispersion.

Appropriate total liquid levels for the small scale tank may be confined to the range H3 to H8, or in geometrically similar systems

$$0.44 < \frac{H}{T} < 1.06 \quad (1)$$

where T is the tank diameter. This corresponds to acceptable total liquid levels between 3 ft. and 6 inches and 8 ft. and 6 inches above vessel floor on the plant scale tanks. Equation (1) excluded total liquid levels H1 and H2 from consideration because the overall density of the aerated liquid in the surface regions is reduced by the entrained air, resulting in a reduced buoyancy effect on the solid particles; the solid particles settle faster under such conditions.

Sampling Technique

The adequacy of the sampling technique in the accessible regions (in terms of sampling) in the small scale tank is shown by Figures 7 and 8, which indicate that the ratio η_{reg}/η_{ave} is near unity for impeller speeds above 370 rpm. This suggests that the samples obtained from the regular single sampling location are approximately equal to the average of those obtained from variously spaced locations throughout the tank for the given H and N. While this may be reassuring it should be noted that only about 10% of the total measurements of the local wt % of the solids are either approaching or exceeding 1 wt %, which is the known overall solids content in the tank. Thin layers of sand were seen occasionally forming doughnut-shaped ring at the center of the tank beneath the impeller blades, particularly at low impeller speeds. These layers quickly fade away or seem to be thrown outward to the tank wall at high impeller speeds. The accumulation of solid particles beneath the agitator hub on the vessel floor and sometimes in the peripheral corner between the bottom and the vertical cylindrical wall of the tank have been observed by Porcelli and Marr¹⁵, Bourne and Sharma¹², and Chudacek¹⁶. Such fillets or deposits are believed to arise because of the low flow velocities in various induced recirculation loops in these regions.

In order to gain insight into the problem of solids entrapped in the inaccessible regions in the tank, a simplified mass balance on sand and coil impediment calculations

have been made in the present study and the results are presented in Appendix B, Table B-1. The mass balance on the solid equated those particles between the tank wall and the outer coil helix ($R - r_{oc}$), plus those between the outer and middle coil helix ($r_{oc} - r_{mc}$), plus those between the middle and the inner coil helix ($r_{mc} - r_{ic}$), plus those between the inner coil helix and the impeller shaft ($r < r_{ic}$), to the known total solids in the tank. Since all the regions except that between the inner coil helix and the impeller shaft are accessible to sampling, the mean wt % of the solids in the latter (inaccessible) region was obtained from this balance (details are shown in Appendix B).

The results show that the mean weight % solids in the inaccessible region (in terms of sampling) between the inner coil helix and the impeller shaft is higher than the average solid concentration (1 wt %) from a factor of 1.22x (i.e., 22 % above the average solid concentration in the case where grossly uniform suspension was approached, $H = H_6$ and $N=686$ rpm) to approximately a factor of 5x for the lowest impeller speeds ($N=100$ rpm). For impeller speeds above the minimum (i.e. 370 rpm), the mean solids concentration in the inaccessible region was as high as 2.55x the known mean concentration of solids in the tank (1 wt %). This finding from the simplified mass balance is reinforced by calculations made of the fraction of the suspended solids whose transportation into the outer regions of the tank was prevented by the impediment offered by the coils. The coil impediment calculations (see Appendix B, Table B-2) also show excess solids retention of 20% above the mean sand concentration in the region between the inner coils helix and the impeller shaft for the case where grossly uniform suspension was approached (i.e., $H = H_6$ and $N=686$ rpm).

Mean radial concentration of solids

The axial distribution of the mean radial concentration of solids ($\bar{\phi}_r$) is shown in Figures 9 to 11 for the liquid depths H_5 , H_6 , and H_7 , respectively. It should be noted that the plots exhibit an intermediate zone characterized by steep curves, followed by a peak corresponding to the maximum solids concentration which occurs at or above 370 rpm, and finally a constant or slightly decreasing curve with the increase in impeller speed. The steep rising portion of the curves indicate that the amount of solids being suspended is a function of the impeller speed. The decreasing portion of the curves show that the centrifugal forces are becoming sufficiently strong to overcome the forces tending to increase the gross uniformity of the solids suspension. Considering the trend of the solids distribution as a

function of the sample height, there is a maximum just above each impeller as previously reported by Nienow¹⁷. The departure at h_5 in Figure 11 may arise from aeration of the surface regions by the upper impeller.

The effects of particle size and density difference on average mixing quality

Figure 12 shows the average mixing quality as a function of the impeller speed for various narrow particle size distributions. The suspension of solids generally decreases with increasing particle size. As shown in Figure 12, for example, the mixing quality average achieved with solid particles of the size between 150 and 180 μm was greater than 95% while the mixing quality average achieved with solid particles of the size between 425 and 600 μm was only 40%. Magelli et al.³ and Nienow¹⁷ reported that the eddies effective for particle suspension have the same size as the solid particles and, therefore, large size particles are much more difficult to homogenize than small particle sizes.

The density difference is another important physical property causing difficulty in the approach to gross homogeneity in solids suspension. Although additional data on different particle densities would be valuable in this study, the importance of any density difference between the small and large scales is accommodated in the following scale-up relation derived by Skelland and Hassan:

$$\frac{N_2}{N_1} = \left(\frac{d_{p2}}{d_{p1}} \right)^{0.15} \left(\frac{\Delta\rho_2}{\Delta\rho_1} \right)^{0.4} \left(\frac{D_1}{D_2} \right)^{0.667} \quad (2)$$

where $\Delta\rho$ is the density difference between the solid and liquid phases, d_p is the suspended particle diameter, and the subscripts 1 and 2 refer to the small and large scales of operation, respectively. It should be noted that the coil impediment effect increases with increasing particle size, thereby increasing the percent of total suspended solids that are stopped by the coil tubing from leaving the inner region of the tank.

Axial and radial distribution of solids

Figures 14 to 16 show the distribution of solids in the radial direction as a function of the vertical sampling heights above the vessel floor, h_1 to h_5 , and at three radial locations, $(R - r_{oc})$, $(r_{oc} - r_{mc})$, and $(r_{mc} - r_{ic})$ corresponding to the regions between the tank wall and the outer coil helix, between the outer and the middle coil helix, and between

the middle and inner coil helix, respectively. As noted in the figures, the solids concentration slightly increases in the region above the impeller blades (for example, from h_1 to h_2) and then generally decreases towards the liquid surface. This trend, although occasionally reverses itself, has been shown by Nienow and Miles¹⁸ for Rushton turbines and for two-blade flat paddles. They concluded that "small impeller clearances (above the vessel floor) produce a flow pattern that scours the base and is efficient for suspension". Readers wishing to speculate on the impeller flow patterns causing these characteristics may be aided by the measured velocity fields above and below a flat-blade turbine in a baffled vessel without coils, presented by McCabe and Smith¹⁹, and Middleton²⁰. Figures 16 to 19 show that the solids distribution in the radial direction is generally higher in the outer region ($R - r_{oc}$) of the tank when both impellers were submerged. The increase in impeller speed tends to reduce both axial and radial variations in the solids distribution.

CONCLUSIONS

1. The abbreviated experimental program conducted in the present study provide sufficiently reliable data for characterization of mixing quality in the small scale-down version of the Separations canyon tank. The data have shown that the minimum impeller speed for just complete suspension of solids is achieved at 370 rpm. Scale-up relationships based on the conservative equal power per unit volume of agitated mixture on two geometrically similar scales of operation suggested a 1.7-fold increase of the plant impeller speed to at least 120 rpm for the attainable condition of just complete suspension but non-uniform dispersion of solids. This scale-up relation accommodates the density difference and particle diameter between the two geometrically similar scales of operation.
2. The variation of average mixing quality with impeller speed show three distinct stages of suspension, corresponding to absence of sufficient radial flow to induce any suspension, transition to just complete suspension, and maximum solids suspension (saturation) marked by strong centrifugal forces overcoming the large scale flow (mean velocities and turbulence) in the tank. Variations with other prevailing conditions (particle size and mean initial concentration) show that the average mixing quality decreases with increasing particle diameter, but only slightly affected by the mean concentration of solids.
3. The distribution of solids as a function of both axial and radial directions show relative scatter of the general data, which may be due to some limitations in the sampling technique. However, recurring trends were identified between the data from adjacent sets

of operating conditions. The mean concentration of solids generally decreases in the radial direction and with sampling height above the vessel floor; a small, but distinct, increase in concentration above each impeller was observed. The approach to gross uniformity of solids suspension increases with increasing impeller speed and the number of impellers.

4. A simplified mass balance and coil impediment calculations show that solids concentration in the inaccessible region (in terms of sampling) between the inner coil and the impeller shaft is higher by a factor of 1.22 to 5 (depending on the impeller speed and liquid level) than the known mean concentration. This would indicate that a new sampling technique is required to explore the solids concentration in the region of impeller shaft. Such a technique will help to avoid dangerously high excessive solids concentrating in this region when the density difference between the solid and liquid or the particle diameter is high.

NOMENCLATURE

B	baffle width, inch
C	impeller clearance from tank bottom, inch
D	impeller blade diameter, inch
D_{ic}	inner coil helix diameter, inch
D_{mc}	middle coil helix diameter, inch
D_{oc}	outer coil helix diameter, inch
d	shaft diameter, inch
d_p	particle diameter of the solids, μm
H	total height of liquid in the tank, inch
h	vertical height of sampling point above vessel floor, inch
L	shaft length, inch
N	impeller rotational speed, rpm
N_m	minimum agitation speed for just complete suspension, rpm
n	number of impellers
p	distance between two corresponding points on the coils, inch
R	radius of the tank, inch
r_{oc}	radius of the outer coil helix, inch
r_{mc}	radius of the middle coil helix, inch
r_{ic}	radius of the inner coil helix, inch
S	distance between impellers on the shaft, inch
T	tank diameter, inch
t	impeller blade thickness, inch
w	impeller blade width, inch
Z	tank height, inch

Greek Symbols

$\Delta\rho$	density difference between the solid and liquid
$\bar{\phi}$	mean concentration of solids in the tank, wt %
ϕ	any local concentration of solids, wt %.
$\bar{\phi}_r$	mean radial concentration of solids, wt %.
$\bar{\phi}_{oc}$	mean concentration of solids between the tank wall and outer coil
$\bar{\phi}_{mc}$	mean concentration of solids between the outer coil and middle coil
$\bar{\phi}_{ic}$	mean concentration of solids between the middle coil and inner coil

η	any local mixing quality, wt %
η_{ave}	average of all measured values of η at all sampling locations
η_{reg}	local mixing quality (η) at the regular sampling single location

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Table 1. Particle Size Distribution of Commercial Sea Sand*

size (μm),	Mesh size	fraction F1, gm	fraction F2, gm	fraction F3, gm	fraction F1, wt	fraction F2, wt	fraction F3, wt	average wt%
< 425	35	4.341	5.8337	4.1957	8.69	11.55	9.92	10.05
< 300	48	6.9321	8.123	7.9157	13.87	16.10	14.38	14.78
< 180	80	20.1435	21.6518	20.2556	40.3	42.89	40.48	41.22
< 150	100	8.7526	7.7333	10.024	17.33	15.32	20.03	17.56
< 75	200	7.5261	6.1993	6.5954	15.06	12.28	13.18	13.51
< 45	325	2.3731	0.9464	1.004	4.78	1.87	1.01	2.35
	Total	50.07	50.47	49.97				

* The sea sand particle density was 2.65 kg/m^3 .

Table 2. Dimensions of Lab Scale and Plant Scale Units*

Unit	lab-scale tank	plant-scale tank	Remarks
Tank			
diameter, T	18	96	plant scale tanks- 8 x 11 feet vessels
height, Z	36	121	
Impeller			
diameter, D	4.5	24	off scale by 0.0625 off scale by 0.0156
width, w	1.0	5	
thickness, t	0.125	0.75	
# of blades	4	4	
Shaft			
diameter, d	0.625	3.375	
length, L	42	226	
Baffles			
width, B	1.25	7	width off-scale by 0.0625
# of baffles	6	6	
Helical coils			0.5" diam. tubing
Inner coils			7 turns
diameter, D _{ic}	8	45	
pitch, p	0.68	3.625	
Middle coils			11 turns
diameter, D _{mc}	10.6	60	
pitch, p	0.8	4.25	
Outer coils			12 turns
diameter, D _{oc}	13.3	75	
pitch, p	1.0	5.375	
Off-bottom clearance, C	1	6	
Distance between impellers, S	9	45	

* all dimensions are in inches

Figure 1. Schematic diagram of the experimental apparatus

Figure 2. A schematic of the grab sampling device (a) normal position, (b) sampling position

Figure 3 . The mixing quality at the regular single sampling location as a function of the impeller speed.

Figure 4. The mixing quality average from variously spaced sampling locations as a function of the impeller speed.

Figure 5. The mixing quality at the regular single sampling location as a function of the impeller speed.

Figure 6. The mixing quality average from variously spaced sampling locations as a function of the impeller speed.

Figure 7. The ratio of the mixing quality at the regular single sampling location to the average from variously spaced locations as a function of the impeller speed.

Figure 8. The ratio of the mixing quality at the regular single sampling location to the average from variously spaced sampling locations as a function of the impeller speed.

Figure 9. Mean radial concentration of solids as a function of the impeller speed for different sample heights.

Figure 10. Mean radial concentration of solids as a function of the impeller speed for different sample heights.

Figure 11. Mean radial concentration of solids as a function of the impeller speed for different sample heights.

Figure 12. The mixing quality average from variously spaced sampling locations as a function of the impeller speed for different particle size distributions.

Figure 13. The mixing quality average from variously spaced sampling locations as a function of the impeller speed for various mean solids concentration.

Figure 14 (a). Solids distribution in the radial direction as a function of the sample height.

Figure 14 (b). Solids distribution in the radial direction as a function of the sample height.

Figure 15 (a). Solids distribution in the radial direction as a function of the sample height.

Figure 15 (b). Solids distribution in the radial direction as a function of the sample height.

Figure 16 (a). Solids distribution in the radial direction as a function of the sample height.

Figure 16 (b). Solids distribution in the radial direction as a function of the sample height.

Figure 17 (a). Solids distribution in the radial direction as a function of the sample height.

Figure 17 (b). Solids distribution in the radial direction as a function of the sample height.

Figure 18 (a). Solids distribution in the radial direction as a function of the sample height.

Figure 18 (b). Solids distribution in the radial direction as a function of the sample height.

Figure 19 (a). Solids distribution in the radial direction as a function of the sample height.

Figure 19 (b). Solids distribution in the radial direction as a function of the sample height.

Figure 20 (a). Solids distribution in the radial direction as a function of the sample height.

Figure 20 (b). Solids distribution in the radial direction as a function of the sample height.

APPENDIX A

Table A-1. Measured local wt % of suspended solids ($\bar{\Phi}=1$ wt %, $n=1$)

H1	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6	Φ_7	Φ_8	Φ_9	Φ_{10}	Φ_{11}	Φ_{12}	Φ_{13}	Φ_{14}	Φ_{15}
N1	0.02	0.02	0.02												
N2	0.11	0.08	0.08												
N3	0.16	0.32	0.23												
N4	0.68	0.54	0.41												
N5	0.84	0.49	0.49												
N6	0.86	0.29	0.37												
N7	0.92	0.44	0.41												
H2	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6	Φ_7	Φ_8	Φ_9	Φ_{10}	Φ_{11}	Φ_{12}	Φ_{13}	Φ_{14}	Φ_{15}
N1	0.01	0.01	0.01	0.03	.03	0.01									
N2	0.1	0.08	0.05	0.1	0.1	0.08									
N3	0.26	0.35	0.35	0.48	0.4	0.36									
N4	0.64	0.5	0.38	0.53	.55	0.51									
N5	0.83	0.71	0.5	0.49	0.4	0.45									
N6	0.9	0.72	0.79	0.88	.88	0.8									
N7	0.91	0.76	0.49	0.76	.76	0.63									

N1=100, N2=200, N3=280, N4=370, N5=528, N6=686, N7=844 rpm

$\Phi_1, \Phi_4, \Phi_7, \Phi_{10}, \Phi_{13}$ refer to vertical sampling points between the tank wall and outer coil,

$\Phi_2, \Phi_5, \Phi_8, \Phi_{11}, \Phi_{14}$ refer to vertical sampling points between the outer and middle coil,

$\Phi_3, \Phi_6, \Phi_9, \Phi_{12}, \Phi_{15}$ refer to vertical sampling points between the middle and inner coil.

Table A-1. Measured local wt % of suspended solids ($\bar{\Phi}=1$ wt %, $n=1$)
(cont.)

H3	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
N1	0.01	0.02	0.03	0.01	.03	0.02									
N2	0.11	0.13	0.1	0.16	.27	0.28									
N3	0.63	0.52	0.44	0.68	.56	0.59									
N4	0.82	0.76	0.59	1.0	.85	0.87									
N5	0.62	0.61	0.71	0.69	.94	0.81									
N6	0.73	0.74	0.5	0.67	.81	0.62									
N7	0.75	0.79	0.56	0.7	.70	0.65									
H4	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
N1	0.02	0.12	0.01	0.02	.01	0.02	0.02	0.01	0.01						
N2	0.65	0.14	0.13	0.32	.44	0.23	0.25	0.34	0.13						
N3	0.49	0.37	0.26	0.69	.88	0.6	0.6	0.55	0.45						
N4	0.89	0.64	0.69	0.9	.88	0.81	0.79	0.7	0.8						
N5	0.84	0.65	0.69	0.75	.96	0.9	0.8	0.7	0.78						
N6	0.87	0.75	0.71	0.81	.76	0.78	0.87	0.62	0.63						
N7	0.77	0.79	0.63	0.58	.63	0.49	0.53	0.58	0.48						

N1=100, N2=200, N3=280, N4=370, N5=528, N6=686, N7=844 rpm

Table A-1. Measured local wt % of suspended solids ($\bar{\phi}=1$ wt %, $n=2$).
(cont.)

H5	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
N1	0.31	0	0.01	0	.04	0.01	0.0	0.0	0.01						
N2	0.5	0.3	0.25	0.36	.37	0.49	0.2	0.18	0.16						
N3	0.65	0.76	0.27	0.92	.95	0.38	0.77	0.51	0.53						
N4	0.78	0.8	0.38	1.05	1.1	0.76	1.06	1.03	0.72						
N5	0.99	0.8	0.38	0.74	.91	0.26	0.98	0.88	0.71						
N6	0.68	0.82	0.72	0.88	.87	1.01	0.88	0.86	0.65						
N7	1.01	0.64	0.88	0.83	.85	0.81	0.89	0.85	0.71						
H6	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
N1	0.57	0.0	0.0	0.0	0.0	0.03	0.01	0.01	0.02	0.0	0.0	0.0			
N2	0.47	0.27	0.07	0.43	0.7	0.34	0.19	0.3	0.27	.07	0.07	0.16			
N3	0.8	0.99	0.64	0.86	1.0	0.65	0.31	0.92	0.6	.21	0.3	0.06			
N4	1.16	0.89	0.91	1.60	1.3	0.74	1.06	0.95	0.78	.57	0.54	0.76			
N5	1.31	0.89	0.81	1.23	1.0	0.98	1.04	1.08	0.31	.53	0.66	0.76			
N6	1.27	0.8	0.77	1.01	.92	0.68	0.96	0.89	0.62	1.8	0.73	0.71			
N7	1.25	0.71	0.53	0.86	.88	0.92	0.97	0.88	0.12	.79	0.77	0.52			

N1=100, N2=200, N3=280, N4=370, N5=528, N6=686, N7=844 rpm

Table A-1. Measured local wt % of suspended solids ($\bar{\phi}=1$ wt %, $n=2$).
(cont.)

H7	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
N1	0.14	0.03	0.12	0.02	.01	0.09	0.02	0.02	0.01	0.0	0.01	0	0.01	0.01	.01
N2	0.77	0.27	0.2	0.2	.35	0.25	0.62	0.44	0.2	0.6	0.38	0.28	0.33	0.26	.25
N3	2.05	0.61	0.53	1.02	.78	0.62	0.96	0.6	0.45	.94	0.87	0.55	0.59	0.76	0.5
N4	1.08	0.81	0.66	1.23	.83	0.72	1.12	0.95	0.59	.96	0.73	0.84	0.72	0.62	.62
N5	0.99	0.86	0.44	0.87	.87	0.79	0.92	0.85	0.72	.93	0.48	0.56	0.73	0.68	.48
N6	0.84	0.7	0.61	0.87	0.8	0.69	0.93	0.76	0.7	.77	0.9	0.43	0.75	0.55	.38
N7	0.79	0.86	0.49	0.98	.88	0.61	0.93	0.71	0.55	.82	0.74	0.4	0.59	0.64	.66
H8	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
N1	0.5	0.04	0.02	0.02	.05	0.02	0.02	0.02	0.01	.02	0.01	0.01	0.01	0.0	0.0
N2	0.55	0.36	0.29	0.59	.59	0.29	0.82	0.39	0.29	.76	0.43	0.29	0.46	0.27	.27
N3	0.96	0.76	0.38	1.25	.79	0.83	1.08	1.07	0.65	1.0	1.01	0.46	0.66	0.61	.52
N4	0.84	0.75	0.41	1.18	1.0	0.74	1.18	1.16	0.96	.18	1.02	0.67	1.04	0.65	.84
N5	0.75	0.82	0.68	0.93	1.1	0.76	1.1	0.94	0.78	.87	0.75	0.54	0.59	0.66	.77
N6	0.71	0.78	0.76	0.91	.82	0.88	1.0	0.86	0.69	.97	0.38	0.57	0.7	0.59	.93
N7	0.7	0.71	0.81	0.91	.92	0.72	1.04	0.91	0.61	.92	0.83	0.42	0.87	1.01	0.8

N1=100, N2=200, N3=280, N4=370, N5=528, N6=686, N7=844 rpm

Table A-2. Measured local wt % of suspended solids ($\bar{\phi}=1.25$ wt %, $n=1$, $H=H3$) -

150-180 μm	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6
N1	0.13	0.02	0.02	0.06	.13	0.09
N2	0.53	0.43	0.40	0.59	.61	0.64
N3	0.98	1.09	0.95	1.23	.38	1.31
N4	1.15	1.09	1.10	1.33	.45	1.48
N5	1.19	1.13	1.10	1.26	.43	1.36
180-300 μm	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6
N1	0.24	0.04	0.02	0.02	0.02	0.03
N2	1.36	0.34	0.32	0.39	0.48	0.45
N3	0.62	0.70	0.60	0.91	1.03	0.89
N4	1.00	0.93	0.80	1.05	1.15	1.17
N5	0.91	0.93	0.92	0.97	1.16	1.03
300-425 μm	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6
N1	0.05	0.01	0.01	0.00	0.01	0.02
N2	0.18	0.19	0.11	0.25	0.24	0.16
N3	2.52	0.71	0.43	0.71	0.86	0.72
N4	0.67	0.63	0.73	0.98	1.14	1.09
N5	0.92	1.07	1.03	1.19	0.99	0.96

N1=100, N2=200, N3=280, N4=370, N5=528, N6=686, N7=844 rpm

Table A-2. Measured local wt % of suspended solids ($\bar{\Phi}=1.25$ wt %, $n=1$, $H=H3$).

425-600 μm	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6
N1	1.06	0.00	0.00	0.00	0.03	0.00
N2	0.13	0.04	0.01	0.10	0.07	0.03
N3	1.42	0.19	0.12	0.35	0.31	0.35
N4	0.06	0.56	0.33	0.73	0.68	0.24
N5	0.07	0.79	0.54	0.79	0.54	0.45

N1=100, N2=200, N3=280, N4=370, N5=528, N6=686, N7=844 rpm

Table A-3. Measured local wt % of suspended solids (n=1, H=H2)

($\bar{\phi}=1$ wt %)	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6
N1	0.01	0.01	0.01	0.03	0.03	0.01
N2	0.10	0.08	0.05	0.10	0.10	0.08
N3	0.26	0.35	0.35	0.48	0.40	0.36
N4	0.64	0.50	0.38	0.53	0.55	0.51
N5	0.83	0.71	0.50	0.49	0.40	0.45
N6	0.33	0.60	0.51	0.75	0.47	0.32
($\bar{\phi}=2.3$ wt %)	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6
N1	0.04	0.05	0.00	0.00	0.02	0.02
N2	0.63	0.16	0.14	0.09	0.17	0.13
N3	1.39	1.10	1.00	1.22	1.31	0.97
N4	1.87	1.98	1.44	1.41	1.69	1.60
N5	1.35	1.58	2.20	1.20	1.25	0.81
($\bar{\phi}=6$ wt %)	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6
N1	0.98	0.02	0.02	0.01	0.01	0.19
N2	2.52	0.09	0.07	0.07	0.08	0.11
N3	1.81	1.93	1.68	1.60	2.50	2.01
N4	3.41	3.99	3.07	4.28	3.07	3.72
N5	1.99	1.26	3.34	4.08	3.94	3.39

N1=100, N2=200, N3=280, N4=370, N5=528, N=686 rpm

Chemical Process Technology Department
Chemical & Hydrogen Technology Section

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APPENDIX B

Material balance on sand in the agitated tank - sample calculation

A mass balance on the sand in the agitated tank was conducted for the case where a more uniform distribution - at least in the axial direction - has been achieved by the impeller speed $N=N6$ (686 rpm) at the total liquid level $H=H6$ (see data in Table 3, appendix A). The following definitions are first given:

- Let the radius of the inner coil helix be r_{ic}
- the radius of the middle coil helix be r_{mc}
- the radius of the outer coil helix be r_{oc}
- the radius of the tank be R
- the mean weight % of the solids for $r < r_{ic}$ be $\bar{\phi}_{ic}$
- the mean weight % of the solids for $r_{ic} < r < r_{mc}$ be $\bar{\phi}_{im}$
- the mean weight % of the solids for $r_{mc} < r < r_{oc}$ be $\bar{\phi}_{mo}$
- the mean weight % of the solids for $r_{oc} < r < R$ be $\bar{\phi}_{ot}$

Using the data from Table 3, Appendix A, for $H=H6$ and $N=N6$, we get

$$\begin{aligned}\bar{\phi}_{im} &= 0.25[0.71+0.62+0.68+0.77] = 0.7 \text{ wt \%} \\ \bar{\phi}_{mo} &= 0.25[0.73+0.89+0.92+0.80] = 0.83 \\ \bar{\phi}_{ot} &= 0.25[1.08+0.96+1.01+1.27] = 1.08\end{aligned}$$

An overall balance on the sand thus equates those between the tank wall and outer coil helix, plus the those between the outer and middle coil helix, plus those between the middle and inner coil helix, plus those between the inner coil helix and the impeller shaft, to the known total sand in the entire tank. Thus

$$\begin{aligned}&\pi(R^2 - r_{oc}^2)H_6\rho_m\bar{\phi}_{ot} + \pi(r_{oc}^2 - r_{mc}^2)H_6\rho_m\bar{\phi}_{mo} \\ &+ \pi(r_{mc}^2 - r_{ic}^2)H_6\rho_m\bar{\phi}_{im} + \pi r_{ic}^2 H_6\rho_m\bar{\phi}_{ic} = \pi R^2 H_6\rho_m\bar{\phi} \quad (B-1)\end{aligned}$$

Since mixture density, ρ_m , is essentially constant at low $\bar{\phi}$, we rearrange equation (B-1) and solve for the unknown $\bar{\phi}_{ic}$. Thus

$$\phi_{ic} = \frac{R^2\phi - (R^2 - r_{oc}^2)\phi_{ot} - (r_{oc}^2 - r_{mc}^2)\phi_{mo} - (r_{mc}^2 - r_{ic}^2)\phi_{im}}{r_{ic}^2} \quad (B-2)$$

Substituting the calculated $\bar{\phi}$ values and the dimensions of r and R from Figure 1 and Table 2 in equation (B-2), yields

$$\phi_{ic} = \frac{9^2(1wt\%) - (9^2 - 6.65^2)1.08 - (6.65^2 - 5.3^2)0.83 - (5.3^2 - 4^2)0.7}{4^2}$$

or

$\bar{\phi}_{ic} = 1.22 \text{ wt \%}$ - i.e., 20% above the average sand concentration in the tank. The results for other prevailing conditions in the tank are given in Table B-1.

Table B - 1. Mean sand concentration ($\bar{\phi}_{ic}$, wt %) between the inner coil helix and the impeller shaft at different liquid levels and impeller speeds.

	H3	H4	H5	H6	H7	H8
N1	4.97	4.97	4.81	4.71	4.92	4.77
N2	4.41	3.70	3.74	3.89	3.38	2.98
N3	2.62	2.77	2.23	2.63	1.38	1.50
N4	1.62	1.77	1.39	1.00	1.40	1.55
N5	2.21	1.86	1.78	1.24	1.82	1.72
N6	2.25	1.86	1.74	1.22	1.98	1.82
N7	2.19	2.55	1.57	1.63	1.99	1.63

Coil impediment calculation

Coil impediment calculation was made to reinforce the results from the simplified mass balance which indicated the directional effect of solids distribution in the tank. The impediment calculation could be made of the fraction of the suspended solids whose transportation into the outer regions of the vessel is prevented by the coil helix. In order to do that an estimate of the collection efficiency, β , versus Stokes Number, Stk , is needed and may be obtained from the work of Helgesen and Matteson²¹ which contains a plot of the fraction of the suspended solids in a flowing stream that is stopped by a transverse cylinder. Suppose a cross-section of the coil in the present study represent a cylinder. Thus for a liquid suspending medium,

$$Stk = \frac{\Delta \rho d_p^2 U_\infty}{18 \mu d_{cyl}} \quad (B-3)$$

Where U_∞ is the free stream velocity approaching a coil of diameter D_c . The calculation of the collection efficiency, β , was made for the largest sand particle size listed in Table 1. namely 425 μm , with the same impeller speed ($N=N_6=686$ rpm) and total liquid level ($H=H_6$) as that used for the sample calculation of the mass balance. Let us define the radial component of the jet stream velocity from the impeller that impinges upon the inner coil, located 4 inches from the tank axis as U_{r4} . Thus

$$U_\infty = U_{r4} = \alpha(\text{impeller tip speed}) = \alpha \pi D N \quad (B-4)$$

The quantity, α , was experimentally measured by Cutter²² as a function of the radial distance in an agitated vessel and a system sufficiently close to ours to be relevant. The ordinate - in Cutter's notation - is the radial component of the local jet stream velocity divided by the impeller tip speed and is thus our α . The significant finding that α is independent of N over the range 200 to 600 rpm probably means that we may regard Cutter's plot (Figure 1BP) as applicable for $N=686$ rpm. At a radial distance of 4 inches, Figure 1B (from Cutter²²) gives $\alpha = 0.34$.

The corresponding Stokes Number is

$$\begin{aligned} Stk &= \frac{(1.65 \text{ gm/cm}^3)(0.0425 \text{ cm})^2 0.34 \pi (4.5 \text{ in} \times 2.54 \text{ cm}) 686 \text{ rpm}}{18(0.01 \text{ Poise}) 1.27 \text{ cm}(60 \text{ sec/min})} \\ &= 1.82 \end{aligned}$$

From Figure 1A (Helgesen and Matteson²¹), $\beta = 0.56$. Repeating the calculations for the five largest particle size in Table 1 gives the results shown in the following table.

Table B - 2. Weight % of total suspended solids stopped by the coils

Particle size, μm	Stk	β	wt % stopped by coils
425	1.82	0.56	$0.56(10.05)=5.63$
300	0.91	0.38	$0.38(14.82)=5.63$
180	0.33	0.16	$0.16(41.43)=6.63$
150	0.23	0.11	$0.11(17.60)=1.94$
75	0.06	0	----- =
			total = 20%

The relative dimensions of our inner coil configuration and impeller blade height, combined with the velocity patterns issuing from the impeller, suggest that only a small section of the coil is involved in such particle interception, because of the narrowness of the radial jet from the impeller blades. Thus, the identical estimates of the excess solids retention in the region between the inner coil helix and the impeller shaft - namely about 20% from both the coil impediment calculations and from our simplified mass balance - may perhaps be regarded as explaining the direction effects we have found concerning solids distribution. Further confirmation would be provided by any demonstration that the larger particles show a disproportionately higher distribution in the regions of the tank. Such a study needs to be done.

Fig. 1A. Theoretical (Ranz and Wong 1952) and experimental (Langmuir and Blodgett 1946, Israel and Rosner 1983) Stokes efficiency curves

Several experimental and theoretical collector efficiency curves have been generated in previous research, as shown in Fig. 1A.

From Helgeson and Matteson (1991)

Photographic measurements have been made of the mean and fluctuating components of velocity of water in a fully baffled stirred tank. Confirmation of much of the photographic data was obtained with a Kiel impact tube.

Fig. 1B Radial profile of mean radial velocity on center line of the impeller stream.

From Cutler (1966)