CE REFRESHER: LIQUID AGITATION/5

Selecting agitator systems to suspend solids in liquids

The settling velocity and equivalent volume are the fundamental relationships in determining the required dynamic response for suspending solids in liquids of low viscosity.

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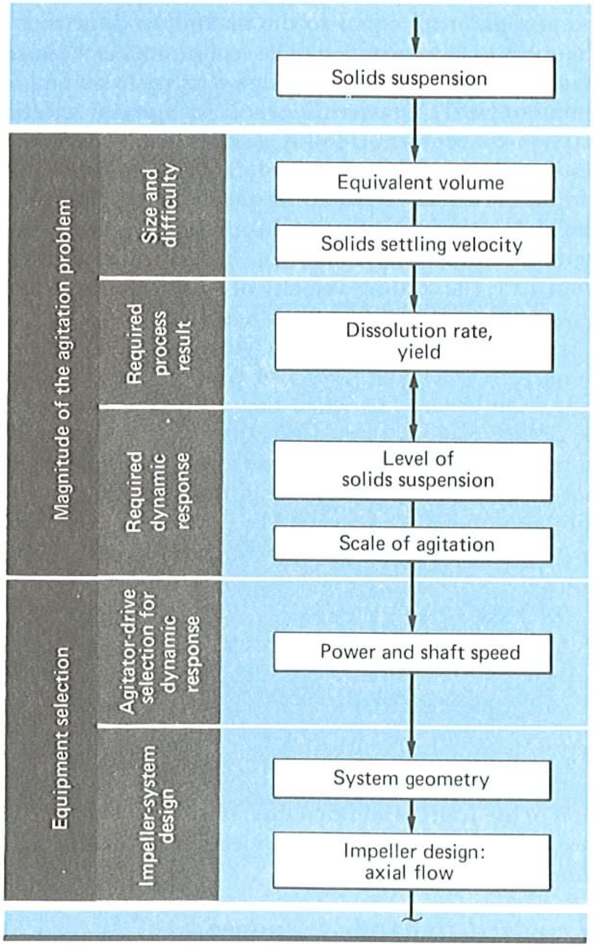
☐ The presence of a two-phase, solid-liquid system classifies an agitation problem as a solids-suspension one. In such problems, the suspension of solid particles having a settling velocity greater than 0.5 ft/min within a continuous liquid phase is the purpose of the agitation.

Examples of systems having slow settling velocities are slurries containing a high concentration of solids, and suspensions of solid particles in a liquid of appreciable viscosity. These systems are treated by the blending-and-motion procedures of the previous article [4].

The level of solids suspension is only one of several design criteria. Surface control, mass transfer and shear rate are other factors for applications involving dry-solids incorporation, solids dissolving, particle-size reduction, leaching and crystallization. Thus, solids-suspension logic (Fig. 1) will provide guidance only in such cases.

Caution should be exercised in applying this solids-suspension procedure to processes where the solid particles are easily suspended in the liquid phase. Typically, this occurs when the settling rate of the solid in the liquid phase is less than 0.5 ft/min.



Design logic for solids-suspension classification **Fig. 1**

Size and difficulty

The size and difficulty of a solids-suspension problem are indicated by the equivalent volume, V_{eq}, and the settling rate of the solid particles, u_d, respectively. The equivalent volume is:

$$V_{eq} = (S_g)_{sl} V \qquad (1)$$

where V is volume of slurry to be agitated, and $(S_g)_{sl}$ is specific gravity of the slurry.

The estimated terminal settling velocity, u_t, of spherical particles is shown in Fig. 2 as a function of particle size and the difference in specific gravity between the solid and the liquid, $[(S_g)_s - (S_g)_l]$, in water [1], and can be used to estimate particle settling velocity in any low-viscosity liquid.

To compute a design settling velocity, u_d, the terminal velocity, u_t, is combined with a correction factor, f_w, from Table I:

$$u_d = u_t f_w \tag{2}$$

Particle settling has been discussed in Part 3 of this series [2]. The terminal settling velocity of a particle is achieved when the drag force (resulting from movement of the particle through the fluid) exactly balances the force due to gravity and no further acceleration of the particle occurs.

The relationship between the drag coefficient and the particle Reynolds number is well known for simple geometries (spheres, cylinders and disks) but not well known for common particle shapes (crushed solids, filter-aid particles, many crystalline forms). In addition, the drag coefficients are only known for particles settling through a stagnant fluid. There is little information available for the drag coefficient of a particle in the flow field produced by a turbine impeller.

The common denominator for the analysis of solids-suspension problems by this procedure will be the determination of the settling velocity of a spherical particle of a diameter equal to the maximum dimension of the solid to be suspended. The technique has been successfully applied to a wide range of particle shapes, and found to yield a conservative basis for agitator selection.

High-concentration-solids slurries exhibit hindered settling characteristics in which the settling rate of individual particles is reduced. Experience has shown that the higher solids concentrations present a more difficult agitation problem. Thus, for concentrations greater than 15%, the settling velocity of single spherical particles is adjusted to higher settling rates.

This design procedure can yield conservative selections even when the shapes of particles deviate markedly from spheres, or when the settling velocity would be reduced significantly from that produced in a low-viscosity system. For these cases, an optimum design may be found by simulating the agitation system. [Simulation and scaleup will be covered in a later article of this series.] The procedure presented here is applicable to a wide range of solids-suspension problems.

A precise statement of a required process response is often very difficult to get, and design of an agitator specifically for that process response even more difficult (see previous articles [3, 4]). All process results obtained with a turbine agitator for solids suspension are due to the distribution of the solid-phase particles within the liquid phase. Hence, the design logic begins with selection of an appropriate dynamic response (level of solids suspension), followed by the selection of turbine agitators for that response.

Required dynamic response

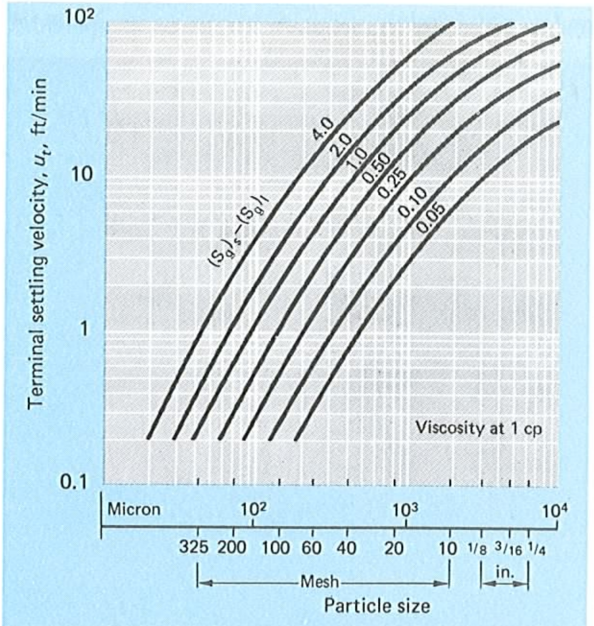
The levels of solids suspension found most useful in process services range from low values where the solid

Correction factor for settling velocity of solids in slurries **Table I**

Solids, %	Factor, f_w
2	0.8
5	0.84
10	0.91
15	1.0
20	1.10
25	1.20
30	1.30
35	1.42
40	1.55
45	1.70
50	1.85

Process requirements set degree of agitation for solids suspension **Table II**

Scale of agitation	Description
1-2	Agitation levels 1-2 characterize applications requiring minimal solids-suspension levels to achieve the process result. Agitators capable of scale levels of 1 will: ■ Produce motion of all of the solids of the design-settling velocity in the vessel. ■ Permit moving fillets of solids on the tank bottom, which are periodically suspended.
3-5	Agitation levels 3-5 characterize most chemical-process-industries solids-suspension applications. This scale range is typically used for dissolving solids. Agitators capable of scale levels of 3 will: ■ Suspend all of the solids of design-settling velocity completely off the vessel bottom. ■ Provide slurry uniformity to at least one-third of fluid-batch height. ■ Be suitable for slurry drawoff at low exit-nozzle elevations.
6-8	Agitation levels 6-8 characterize applications where the solids-suspension level approaches uniformity. Agitators capable of scale level 6 will: ■ Provide concentration uniformity of solids to 95% of the fluid-batch height. ■ Be suitable for slurry drawoff up to 80% of fluid-batch height.
9-10	Agitation levels 9-10 characterize applications where the solids-suspension uniformity is the maximum practical. Agitatiors capable of scale level 9 will: ■ Provide slurry uniformity of solids to 98% of the fluid-batch height. ■ Be suitable for slurry drawoff by means of overflow.



Particle size determines terminal settling velocity of solids in low-viscosity liquid **Fig. 2**

particles are incompletely suspended, to high values where the slurry is practically homogeneous.

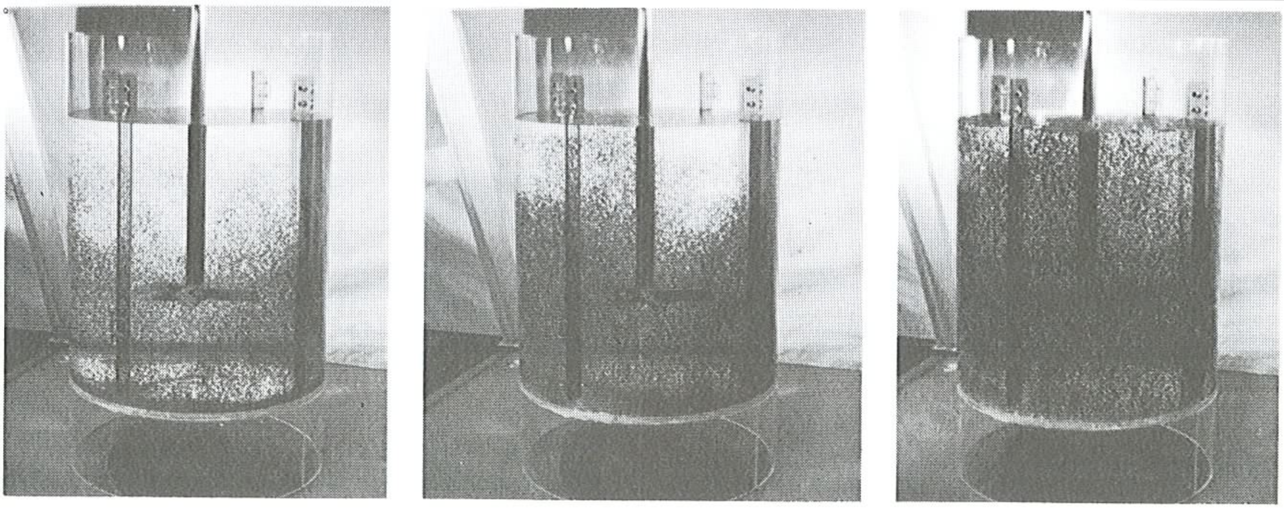
Differing solids-suspension levels are shown in Fig. 3. The vessel has a capacity of 160 gal, and contains a 15%-by-weight slurry consisting of 20-mesh plastic beads in water. The beads have a settling velocity of 25 ft/min [as obtained from Fig. 2, Table I and Eq. (2)]. Fig. 3a demonstrates a low level of dynamic response where the solid particles form unstable fillets on the tank bottom for a time but are then periodically swept off the bottom. Fig. 3b shows a solids-suspension level where all solid particles are swept off the vessel bottom. Fig. 3c indicates a response level where the solid particles are homogeneously distributed to 98% of the batch height.

Nomenclature

D	Impeller diameter, in
f_w	Correction factor for settling velocity
H_p	Prime-mover power, hp
L	Shaft length, in
N	Shaft speed, rpm
n	Number of impellers
S	Impeller spacing, in
$(S_g)_l$	Specific gravity of solids-free liquid
$(S_g)_s$	Specific gravity of solid particles
$(S_g)_{sl}$	Specific gravity of slurry
T	Vessel diameter, in
u_d	Design settling velocity, ft/min
u_t	Terminal settling velocity, ft/min
V	Volume, gal
V_{eq}	Equivalent volume, gal
Z	Fluid-batch depth, in

Observation of Fig. 3a and 3b shows that the particles are not at a uniform concentration as a function of depth. In other words, the turbine agitator produces large eddies, which will occasionally lift a large population of beads in a spout to a higher elevation in the tank. The eddy then decays and the solid particles fall back to lower elevations. Due to this fluctuation, a quantitative, steady-state solids concentration at a particular elevation is impossible to define.

Various definitions of solids-suspension levels are discussed in the "Chemical Engineers' Handbook" [*1*]. As



a. Unstable fillets are on vessel bottom (Scale of agitation = 1)

b. Particles swept off vessel bottom (Scale of agitation = 3)

c. Solids are homogeneously distributed (Scale of agitation = 9)

Intensity of agitation affects magnitude of solids suspension and yields differing dynamic-response levels **Fig. 3**

Prime-mover power and shaft speed (hp/rpm) for solids suspension ($u_d = 10$ ft/min) Table III

Scale of Agitation	Equivalent volume, gal							
	500	1,000	2,000	5,000	15,000	30,000	75,000	100,000
1	1/350	1/190	2/190	5/125	10/84	20/100	50/68	60/84
			1/100	3/84	7.5/68	15/68	40/84	50/68
				3/68	5/45	10/45	40/56	40/56
				2/45	3/37	7.5/37	20/37	30/37
2	1/230	1/100	2/125	7.5/125	20/100	40/84	100/100	125/68
			1.5/84	5/100	15/68	30/68	75/68	100/56
				5/84	10/45	25/56	60/56	75/45
				3/56	7.5/37	20/37	50/45	75/37
3	1/190	2/190	2/84	3/37	25/100	60/125	100/68	75/30
			1.5/56		20/68	50/100	100/56	60/20
					15/56	50/84	75/45	
					10/37	30/45	60/30	
4	1/155	2/155	5/155	7.5/84	30/100	60/84	150/84	200/68
		1.5/100		5/56	25/84	50/68	125/68	150/56
					15/45	40/56	75/37	125/45
						30/37		100/30
5	1/125	1.5/84	3/84	15/155	40/100	75/100	75/30	300/100
		2/125		10/100		60/68	60/20	250/84
				7.5/68		50/56		150/45
				5/45		30/30		125/37
6	1/100	2/100	5/125	10/84	40/84	75/68	250/84	300/68
		1.5/68	3/68		30/68	60/56	200/68	250/56
			3/56		25/56	50/45	150/45	200/45
			2/45		20/37	40/37	125/37	150/37
7	2/190	2/84	7.5/155	15/84	60/125	100/68	350/84	200/30
		1.5/56	7.5/125	10/56	50/100		200/45	150/30
			5/84	7.5/45	40/56		150/37	150/25
				7.5/37	30/45		100/20	
8	1.5/84	3/84	7.5/84	25/125	75/100	125/68	300/68	400/56
	2/125		5/56	20/100	60/84	100/56	250/56	350/45
				15/68	50/68	75/45	150/30	300/45
				10/45	30/37	75/37	125/25	250/37
9	2/84	7.5/155	15/155	40/155	75/68	75/30	400/56	
		5/125	10/100	30/100	60/56		300/45	
		5/100	7.5/68	25/84	50/45		250/37	
		3/68		20/68	40/37		200/30	
10	5/125	7.5/125	20/100	50/100	150/84	250/84	600/84	
		5/84	15/84	40/84	125/68	200/68	500/68	
			10/84	30/68	100/56	150/45	350/45	
				25/56	75/45	125/37		

noted, sampling for solids concentration is difficult because of the disruption of the flow pattern by the sampling device.

For the procedures in this article, the level of solids suspension is determined as being visual uniformity at or below a given fluid-batch elevation. Visual-uniformity definitions are used because of sampling inapplicability and the time variation in solids concentration due to fluid motion.

Scale of agitation

It is convenient to express the dynamic response for solids suspension by an agitation scale ranging from 1 to 10. Increasing scale levels, as shown in Table II, indicate increasing solid-particle uniformity within the agitated slurry. Performance criteria are enumerated at several scale levels within this table. Each increment of scale will provide a distinct difference in the solids-suspension level.

Prime-mover power and shaft speed (hp/rpm) for solids suspension (u_d = 25 ft/min) **Table IV**

Scale of agitation	Equivalent volume, gal							
	500	1,000	2,000	5,000	15,000	30,000	75,000	100,000
1	1/230	2/190 1/190 1/100	2/125 2/84 1.5/84 1.5/56	5/125 3/84 3/68 2/45	20/100 15/68 10/45 7.5/37	30/100 25/84 20/68 15/45	75/100 60/56 50/45 40/37	125/68 100/56 75/68 75/37
2	1/190	2/125	3/84	15/155 10/100 7.5/68 5/45	30/100 25/84 20/68 15/45	60/84 50/68 40/56 30/37	150/84 125/68 100/56 75/37	250/84 200/68 150/45 125/37
3	1/100	1.5/84	5/125 3/68 2/45	10/84	40/84 30/68 25/56 20/37	75/84 60/56 50/45 40/37	250/84 200/68 150/56 125/45	400/100 200/45 150/37 100/20
4	2/190	2/84 1.5/56	7.5/155 5/100 3/56	7.5/45	60/125 50/100	75/68	300/100 150/45 125/37	300/68 250/56 150/30 125/25
5	2/155	2/68 2/56	7.5/125 5/84	15/84 10/56 7.5/37	75/125 50/84 30/45	100/68	400/100 200/45 150/37 100/20	150/25
6	2/125 1.5/84	3/84	5/56	25/125 20/100 15/68 10/45	60/84 50/68 40/56 30/37	125/68 100/56 75/45 75/37	300/68 250/56 150/30 125/25	400/56 350/45 250/37 200/30
7	2/84	7.5/155 5/125 5/100 3/68	15/155 10/100 7.5/84 7.5/68	30/100 25/84 20/68 15/56	75/68 60/56 50/45 40/37	75/30	400/56 300/45 250/37 200/30	
8	3/100	7.5/125 5/84	10/84	60/155 40/100 30/68 25/56	100/68 75/56	250/84 200/68 150/45 125/37	600/84 500/68 350/45	
9	5/155	10/125 7.5/100	15/84	75/190 60/125 50/100 40/84	150/84 125/68 100/56 75/45	400/100 350/84 200/45 150/37		
10	7.5/155 5/125	15/155 10/100	30/155 25/125 20/100	75/125 75/100 60/84 50/84	300/100 250/84 200/68 150/56	400/56 300/68		

The dynamic-response levels shown in Fig. 3a, 3b and 3c would be characterized by scale levels of 1, 3 and 9, respectively. These levels are specific visual descriptions for any settling velocity, and are not specific to the settling velocity of the material in the tank.

Selection of agitator drive

Prime-mover power and agitator shaft speed make up the principal element for the agitator-design procedure. Selection tables list the power/speed relation as a function of equivalent volume, settling velocity of the solids, and scale of agitation. Condensed versions of the drive-selection tables are included as Tables III and IV for settling velocities of 10 ft/min and 25 ft/min, respectively. For an analysis of the power/speed relation for turbine agitators handling solids-suspension problems, see the material in the accompanying box on p. 149.

The powers and shaft speeds in these tables reflect the use of standard, commercially available, turbine agitators. The prime-mover powers are for standard electrical motors; the shaft speeds are those obtained by using the speeds of standard motors in combination with standard AGMA (American Gear Manufacturers Assn.) gear ratios. The notation 10/84 means a 10-hp motor in combination with a shaft speed for the agitator of 84 rpm.

Impeller-system design

After selecting suitable drives, the turbine agitators must be equipped with the correct impeller system. This system includes the type, number, batch location and diameter of all turbines, as well as an appropriate baffling system.

The basic impeller for solids suspension is the pitched-blade turbine. This turbine and the axial-flow pattern it produces were previously described in Part 1 of this series [3].

The number and position of the pitched-blade turbines for solids suspension are shown in Table V as a function of batch configuration. (Note that the turbine elevations are somewhat lower than those for blending and motion [4].)

To estimate the diameter of pitched-blade turbines for the desired dynamic response, we use:

$$D = 394\left(\frac{H_p}{nN^3(S_g)_{sl}}\right)^{0.2} \qquad (3)$$

It is not necessary to correct the diameter obtained from Eq. (3) for the Reynolds number because solids-suspension agitation will not be applied to liquid phases at high viscosities.

For solids suspension, four baffles are positioned every 90° in the vessel. The baffles should have a width equal to one-twelfth the vessel's diameter, and should have an offset from the vessel wall equal to one seventy-second of the vessel's diameter. This gap between the vessel wall and the baffles prevents dead spots and solids accumulations.

Dry-solids incorporation

A common problem encountered in the chemical process industries is the incorporation of dry solids into a liquid. The difficulty of the problem is influenced by (a) particle size and wetting characteristics of the solid, (b) rate and manner in which the dry solid is charged to the liquid surface, and (c) amount and type of motion at the agitated surface.

If the dry solids are very fine, difficult to wet, or added at a very high rate, several techniques for promoting solids makedown are available. A usual procedure is to provide an additional pitched-blade turbine (near the liquid surface) than is called for by batch-geometry criteria. It is customary to locate this impeller at a distance equal to one-half the impeller diameter below the liquid surface. Removing baffles from the upper portion of the fluid batch creates a vortex that can be of significant help to solids incorporation.

The more difficult a dry solid is to make down into a slurry, the higher the scale of agitation. In some cases,

Design analysis for power and speed relations for solids suspension

A 5,000-gal vessel requires an agitator that will provide a solids-suspension scale level of 5. Specific gravity of the 1,000-micron (μm) solids is 1.255, and that of the solids-free liquid is 0.955. The slurry contains 15%-by-weight solids, and has a slurry gravity of 1.0. Let us select agitators that will provide a solids-suspension scale level of 5.

We begin by calculating the terminal settling velocity, u_t, of the solids. The difference in specific gravity between the 1,000-μm solids and the solids-free liquid is 0.3. We now find u_t from Fig. 2 as 10 ft/min. To correct for the 15%-solids concentration, we consult Table I and find that $f_w = 1.0$. Hence, the design settling velocity, u_d, from Eq. (2) becomes (10)(1) = 10 ft/min.

We now assume that the slurry depth, Z, in the vessel is equal to the vessel's diameter, T, and also select a representative value for the ratio of the impeller diameter, D, to vessel diameter, T, of 0.3. A volume of 5,000 gal corresponds to 5,000/7.48 = 668.5 ft^3. Since T must equal Z, we substitute in the following relation to find T:

$$V = (\pi/4)(T^2)(Z) = (\pi/4)T^3$$

$$668.5 = (\pi/4)T^3$$

$$T = 9.48 \text{ ft, or } 113.76 \text{ in}$$

Since D/T was assumed to be 0.3, the impeller diameter, D, becomes 0.3(113.76) = 34.13 in.

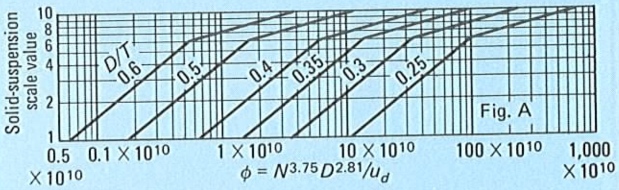


Fig. A

In order to establish the agitator's shaft speed, we will use the relations of Fig. A, in which the solids-suspension scale values are plotted as a function of agitator speed, turbine diameter and design settling velocity for single pitched-blade turbines in vessels where $T = Z$. In this problem, we were given a scale level of 5 and assumed a $D/T = 0.3$. For these conditions, we obtain from Fig. A, the value for ϕ as 27×10^{10}.

We now calculate the required shaft speed from:

$$\phi = N^{3.75}D^{2.81}/u_d$$

where N is shaft speed, rpm; D is impeller diameter, in; and u_d is design settling velocity of solids, ft/min. Hence:

$$27 \times 10^{10} = N^{3.75}(34.13)^{2.81}/10$$

$$N = 147.54 \text{ rpm}$$

We obtain the prime-mover power associated with this speed by substituting into Eq. (3), and rearranging it to solve for H_p:

$$H_p = \frac{(1.0)(147.54)^3(34.13)^5(1)}{(394)^5} = 15.66 \text{ hp}$$

The 15.66 hp and 147.54 rpm calculated for this example are not available in commercial equipment. Essentially, we could repeat the preceding calculations at other D/T ratios in order to obtain a standard power and speed combination. However, it is more convenient to begin with commercially available equipment, and then assign the power/speed combination a place in an equivalent-volume, settling-rate, scale-level array such as the condensed Tables III and IV of this article.

Number of impellers for solids suspension **Table V**

Impellers, no.	Impeller clearance*		Maximum ratio, Z/T
	Bottom	Upper	
1	$Z/4$	—	1.2
2	$T/4$	$(2/3)\ Z$	1.8

*Z = liquid depth; T = vessel diameter.

makedown (not solids suspension) is the controlling factor in selecting a turbine agitator.

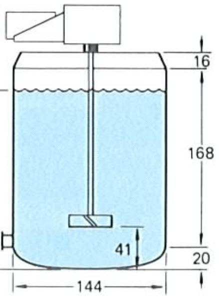
Settled-solids resuspension

Another common problem occurs when the agitator must resuspend a settled bed of solids. The nature of the settled bed affects the ability to resuspend it. Fine solids tend to settle very densely. Particle shape, chemical bonding, particle cohesion, and duration of the settled condition, can also influence the problem. When this occurs, it can be difficult, if not impossible, to resuspend the particles and to reestablish the original level of solids suspension. Resuspension problems may also require higher scales of agitation than are needed to maintain the suspension.

Example illustrates design analysis

The problems associated with solids suspension, and the logic needed for selecting an agitator and its drive, have now been analyzed and evaluated in accordance with the sequence of Fig. 1. Let us now solve a typical problem involving solids suspension to illustrate the techniques previously described.

A 12-ft-dia. by 14-ft straight-side surge vessel in a continuous-process plant requires an agitator. The vessel has a standard, dished, bottom head, an open top, and a 16-in-high beam support for the agitator. The bottom head is 20 in deep and has a volume of 735 gal. The 30%-by-weight solids slurry has a specific gravity of 1.34. Fluid depth in the vessel will be a maximum of 163 in. The particles are 50 mesh and have a specific gravity of 2.6, while that of the liquid is 1.1. Liquid viscosity is 1 cp. The required process result is to provide a uniform effluent concentration from the exit nozzle located near the lower tangent line of the vessel, as shown in the sketch:



All dimensions are in inches.

We calculate the equivalent volume of the slurry by first finding the capacity to which the vessel is filled. The size of the fluid batch is found by adding the capacity of the straight side and the dished-bottom head from:

$$V = \frac{\pi}{4}\left(\frac{144}{12}\right)^2\left(\frac{143}{12}\right)(7.48) + 735$$

$$V = 10{,}816 \text{ gal}$$

By substituting into Eq. (1), we find:

$$V_{eq} = 10{,}816(1.34) = 14{,}493$$

We now calculate the terminal settling velocity of the solids. The difference in specific gravity between the solids and the solids-free liquid is $(2.6 - 1.1) = 1.5$. And, from Fig. 2, we find u_t as 7.7 ft/min. From Table I, we obtain the correction factor, f_w, as 1.30. Substituting into Eq. (2) yields the design settling velocity, u_d, as 10 ft/min.

The required process result can be identified with a solids-suspension scale level of 3 from Table II. For a scale level of 3 and $V_{eq} = 15{,}000$ gal, we find the combination of power and shaft speed as 25/100, 20/68, 15/56 and 10/37 from Table III. These are the turbine-agitator drives that are capable of solving the process problem.

Since the ratio of $Z/T = 163/144 = 1.13$, we consult Table V to find that one pitched-blade impeller is required having a bottom clearance of $Z/4 = 163/4 = 41$ in. The overall shaft length, L, is 163 in. For each of the agitator drives previously selected from Table III, we determine the estimated turbine diameter by substituting into Eq. (3). For the power/speed combination of 25/100, we find:

$$D = 394\left[\frac{25}{(1)(100)^3(1.34)}\right]^{0.2} = 45 \text{ in}$$

Similar calculations for the power/speed selections of 20/68, 15/56 and 10/37 yield impeller diameters of 54, 57 and 67 in, respectively.

The number of baffles is 4, with a width of $T/12 = 144/12 = 12$ in, a length of 168 in, and a clearance from the tank wall of $T/72 = 144/72 = 2$ in.

Selection of the optimum turbine agitator for this service will be based on completion of the mechanical design, followed by an economic evaluation.

References

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Lewis E. Gates — For biography, see *Chem. Eng.*, Dec. 8, 1975, p. 114.

Jerry R. Morton — For biography, see *Chem. Eng.*, Apr. 26, 1976, p. 110.