Mixing and Solid Suspension by Up-Down Agitators in a Slab Tank

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Slab tanks, shown in Figure 1, are used routinely at SRP as the tank geometry for many processes including dissolution, precipitation, crystallization, blending, and solid suspension. Typical slab tanks are rectangular with length-height-width proportions of 7-6-1. The geometry is a result of nuclear safety requirements. Impeller designs, used in up-down agitation, can closely match the slab tank geometry. As a result, up-down agitation could be used for process applications in slab tanks if sufficient documentation is obtained.

The up and down motion of the impeller and shaft in Figure 1 was produced by a crank wheel located above the tank. The stroke frequency of the up-down motion was analogous to the impeller rotational speed in rotary mixing. The major geometric variables of the impeller were the amplitude, a, of the up-down motion, the blade width, w, and the general shape of the impeller. Secondary geometric variables included the off-bottom blade clearance, c, the liquid height, h, and the blade length.

The objective of this study (Ramsey, 1988) was to document mixing and solid suspension capabilities of up-down impellers. The effects of impeller design, stroke frequency, n; amplitude, a; blade width, w; and liquid depth, h, were studied. Ancillary objectives of the work were to investigate the similarities between up-down agitation and rotary agitation and to study the use of full-tank impellers, typical of laminar mixing designs, in turbulent mixing applications.

Background

Mixing times

In mixing studies where an effective impeller is used, the product of impeller rotational speed, N, and mixing time, θ, is the number of revolutions to mix a tracer injection throughout a vessel:

$$N\theta = Ho \tag{1}$$

where Ho is the homogenization number, which varies from 20 to 80 for efficient rotary geometries. For a fixed geometry, Ho is constant under either laminar or turbulent rotary mixing conditions. In studies of different geometries, Ho is a function of geometry. In the transition regime, Ho is dependent upon geometry, the fluid mechanics, and fluid properties.

Studies involving the mixing capabilities of up-down agitators include Bates et al. (1966) which discussed a perforated reciprocating plate. Effective mixing at high stroke frequencies was obtained, but no quantitative results were given. Nagata et al. (1972), working with high viscosity fluids, showed that up-down agitation provided mixing times comparable to those obtained with the best rotary designs. Murakami et al. (1980) combined up-down and rotary motion through a crank-gear system and measured mixing times for different impellers. The addition of up-down motion led to improvements in mixing performance. Nagata et al. (1972) and Murakami et al. (1980) found Eq. 1 to hold for up-down designs in the laminar regime.

Solid suspension

Most research on solid suspension in rotary mixing concerns the minimum impeller rotational speed, n_s, necessary to produce complete off-bottom suspension. The minimum rotational speed permits particles to remain on the tank bottom for only 1 to 2 s. An accepted correlation for n_s can be written in a power law

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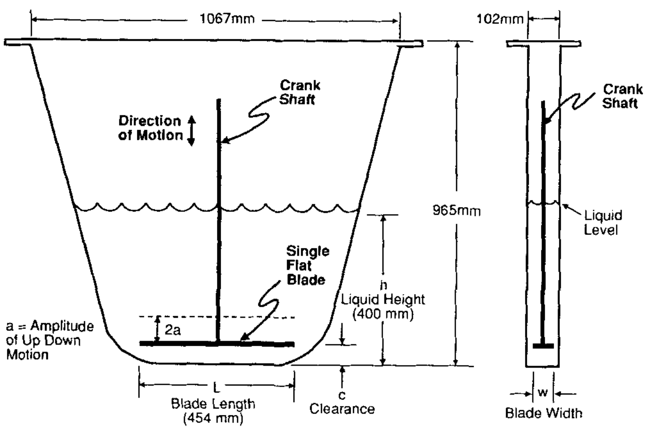

Figure 1. Slab tank geometry with a single flat blade impeller.

form:

$$n_s = S\nu^{0.1} d_p^{0.2} (g\Delta\rho/\rho_L)^{0.45} X^{0.13} D^{-0.85} \tag{2}$$

where S is a significant function of the D/T and C/T ratios (Zwietering, 1958). The S parameter accounts for the relative size of the impeller to the tank and the proximity of the impeller to the tank bottom. With an increase in the impeller to tank diameter ratio (D/T), the impeller is relatively more effective at solid suspension which causes a decrease in n_s. A decrease in the impeller clearance to tank diameter ratio (C/T) usually causes a decrease in n_s, since the impeller is relatively closer to the vessel bottom. The exponent on weight fraction, X, is not fixed and is known to vary between 0 and 0.3 (Tay et al., 1984).

In up-down agitation for solid suspension, Tojo et al. (1981) assumed that the mechanism responsible for suspension in both rotary and up-down systems was the same. They assumed that the energy imparted by the rotating impeller or vibrating disk induced an axial velocity which suspended the particles. Tojo et al. found roughly the same effects of liquid viscosity, particle diameter, and density difference as stated in Eq. 2 but obtained a -1.6 exponent for the impeller diameter.

Studies of up-down agitation which couple solid suspension and mixing times in a nonstandard geometry are unavailable.

Experimental Program

Seven different blade geometries, shown in Figure 2, were studied. Blade width was varied from 36 to 85 mm. The blade thickness, the projected horizontal blade length and tank width were fixed at 9.53 mm, 454 mm, and 102 mm, respectively. The minimum off-bottom blade clearance was 20 mm measured from the tank centerline. Blade number, blade angles (i.e., pitch and roll), blade spacing and off-bottom clearance were varied as shown in Figure 2.

Mixing times were obtained by dispersing dye. A device injected an equal volume ratio (0.2 mL/L) of dye at the same location for each test. No substantial momentum was added to the liquid in the tank during injection. The process fluid was tap water which remained at a constant temperature during the experiments. Mixing times from dye injection on either side of the tank were equivalent.

The full-cycle stroke frequency, n, ranged from 0.7 to 2.6 Hz,

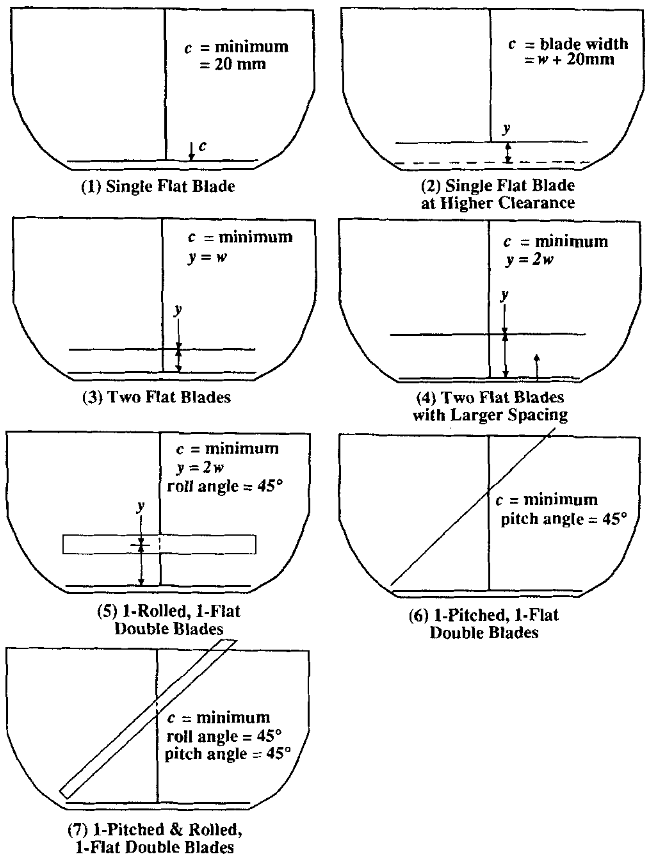

Figure 2. Different impeller configurations studied.

and the stroke amplitudes were 25, 38 and 51 mm. The stroke length of the impeller in the slab tank was twice the amplitude. The impeller Reynolds Number was defined as 4 naw/ν and ranged from 2,500 to 45,000. In most tests, the flow contained a variety of length scales and was turbulent at high Reynolds numbers. The transition mixing regime occurred at low Reynolds numbers. The majority of tests were conducted with a tank volume of 29 L at a liquid depth, h, of 400 mm measured from the tank centerline. The effect of liquid depth was studied for the two different blade geometries at the depths of 300 mm and 480 mm. The tank was considered mixed when the dye concentration was uniform throughout the tank as recorded on the videotape. This method was verified by direct visual inspection. The standard deviations in Ho were usually less than 10% of the mean value.

Solid suspension

These studies were performed using sand and tap water. The density and mean particle size of the sand were 2.63 g/cm^3 and 160 μm, respectively. Particle sizes ranged from 75 μm to 300 μm. All solid suspension studies had one flat blade at the minimum off-bottom clearance of 20 mm measured at the tank centerline. Two blade widths, 47 and 74 mm, and the same amplitudes and liquid heights as above were studied. The frequency at which no particle remained on the tank bottom longer than 1 s was recorded as the complete suspension frequency, n_s. The solids concentration was varied from 0.1 to 20.0 wt. % for a liquid volume of 29 L. The effect of liquid depth was studied by lowering the liquid level to 180 mm. The depth change increased the maximum solids concentration to 57.2 wt. %. This weight percent posed no difficulties in solids suspension, since the flat blades were always started at minimum clearance. The maximum height, which the slurry obtained, was recorded (Ramsey, 1988), but is not reported in this work.

Results

Mixing time studies

The bulk motion of the dye, shown in Figure 3, was the same for all geometries studied. The bulk motion was not discernible after one stroke (Step 1), but became obvious as mixing progressed. The mixing depended upon the number of strokes. The design and operational effects on mixing times will be expressed in terms of their effect on this bulk motion and the homogenization number, *Ho*.

Simplest geometry

A single flat blade at minimum clearance was the simplest geometry. The blade width and amplitude were the most important lengths and fixed the major geometric features of the up-down agitator. *Ho* data for this system are shown in Figure 4. The minimum in *Ho* at a dimensionless blade width, w/T, of 0.75 was caused by two opposing effects. Below w/T of 0.75, increasing the blade width increased the bulk circulation which caused lower *Ho* values. Above w/T of 0.75, wall effects and wall friction became significant and reduced the bulk circulation. As the blade width approached the tank thickness, circulation approached zero and the homogenization number became very large. Minimums in *Ho* are common in mixing when full-tank impellers are used (Takahashi et al., 1982; Kappel, 1979). In terms of the hydrodynamics, the minimum probably occurred because of a size balance between the blade vortices forming and shedding from behind the blade, the size of the flow into these vortices and the draft flow of the blade.

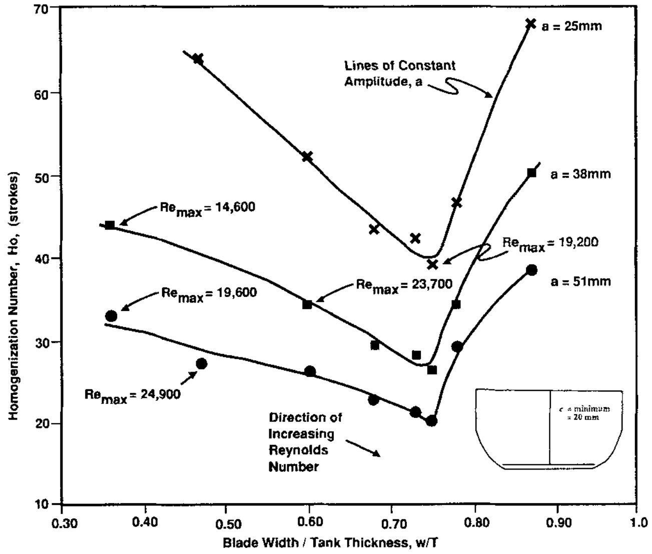

Figure 4. Effect of blade width upon the homogenization number for different amplitudes for a single flat blade geometry: liquid height = 400 mm, minimum off-bottom clearance.

The data in Figure 4 also show that, as the stroke amplitude increases, the effect of the amplitude becomes less. Although further data are needed, the effect of increasing stroke amplitude reaches an asymptotic limit where the mixing effectiveness of long strokes becomes independent of the stroke length. Practical considerations of machine design restrict the use of high amplitudes.

Ho correlation

From Figure 4, operations at low amplitude or above w/T of 0.75 were considered undesirable. The low amplitude data were in the transition mixing regime which is undesirable for mixing. Wall effects and high friction were undesirable. Operation at the minimum was also considered too restrictive. In the region of choice, $0.35 < w/T < 0.75$ and $0.090 < a/h < 0.13$, the homogenization number was correlated by:

$$Ho = 2.13(w/T)^{-2/3}(a/h)^{-1.0} \tag{3}$$

This correlation has the same basis as correlations for cylindrical tanks reported by Prochazka and Landau (1961, 1961), Hiraoka and Ito (1977), Shiue and Wong (1984), and Sano and Usui (1985). The homogenization number is proportional to the ratio of the volume being mixed, i.e., $T^{2/3}h$, to the volume of the mixer, i.e., $w^{2/3}a$.

The effect of liquid height was not as clear as Eq. 3 indicates. Marr and Johnson (1961) in cylindrical systems showed that *Ho* changed abruptly with changes in liquid height because of

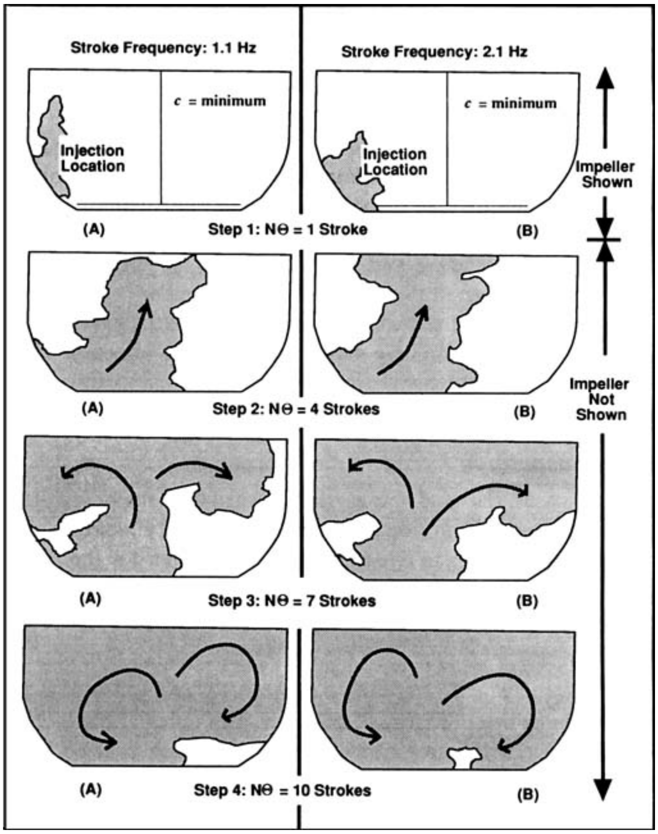

Figure 3. Idealized dye dispersion for stroke frequencies of: (A) 1.1 Hz and (B) 2.1 Hz with stroke amplitude = 38 mm, liquid height = 400 mm.

changes in flow patterns. These same effects as well as compartmentalization were observed in this study.

Blade widths above w/T of 0.75 were not studied further because of the substantial wall effects.

Ho data in more complicated geometries

The homogenization numbers in Figure 5 were obtained for different blade geometries as a function of a/T at $w/T = 0.725$ just below the minimum. (The ratio of T/h was 0.255 in this study.) The lowest homogenization number, $Ho \simeq 18$, was obtained using a single blade with the widest blade width (i.e., $w/T = 0.725$) at the largest blade amplitude studied.

The effects of geometry on Ho in Figure 5 can be explained in terms of the effect of geometry on bulk circulation. Increasing amplitude decreased Ho. For a given geometry, an increase in amplitude produced stronger bulk motion in the tank. An increase in the off-bottom blade clearance, c, produced an increase in Ho (poorer mixing). With the blade set at the lowest clearance, the bulk flow was forced upwards in the middle of the tank. When the clearance was increased, the flow was forced upwards not only in the middle, but also up and down along the curved sides of the tank, resulting in weaker bulk circulation. An increase in blade number to two blades (blade spacing = blade width) caused an increase in Ho (poorer mixing). A weaker circulation was produced by an increase in blade number, because the upper blade interfered with the flow produced by the motion of the lower blade. An increase in the distance between the two blades produced more interference, which led to even weaker bulk circulation and a further increase in Ho (poorer mixing).

Roll and pitch blade angles for the impellers shown in Figure 6 can affect Ho. The two pitched geometries had lower Ho values than the single flat blade geometry for the same blade width and stroke amplitude. The addition of a pitched angled blade did not disrupt the bulk circulation, but enhanced it by increasing mixing in both the vertical and horizontal directions. Rolling or

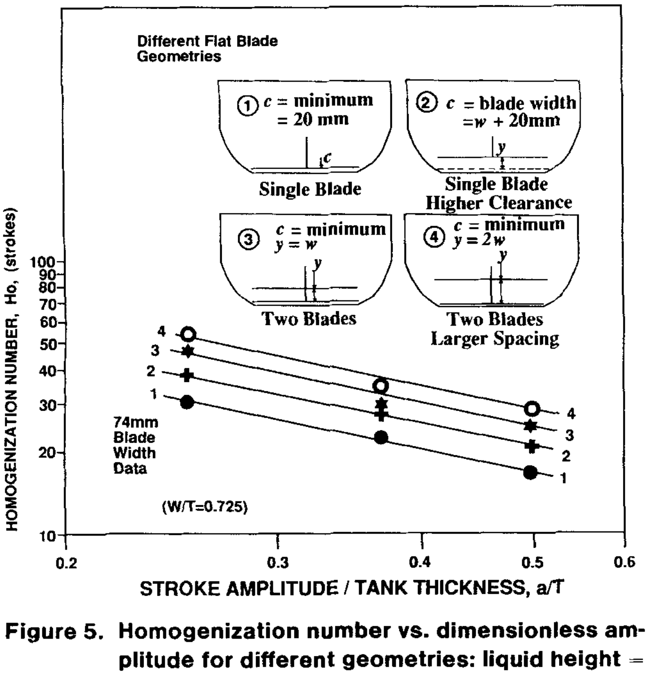

Figure 5. Homogenization number vs. dimensionless amplitude for different geometries: liquid height = 400 mm, blade width = 74 mm.

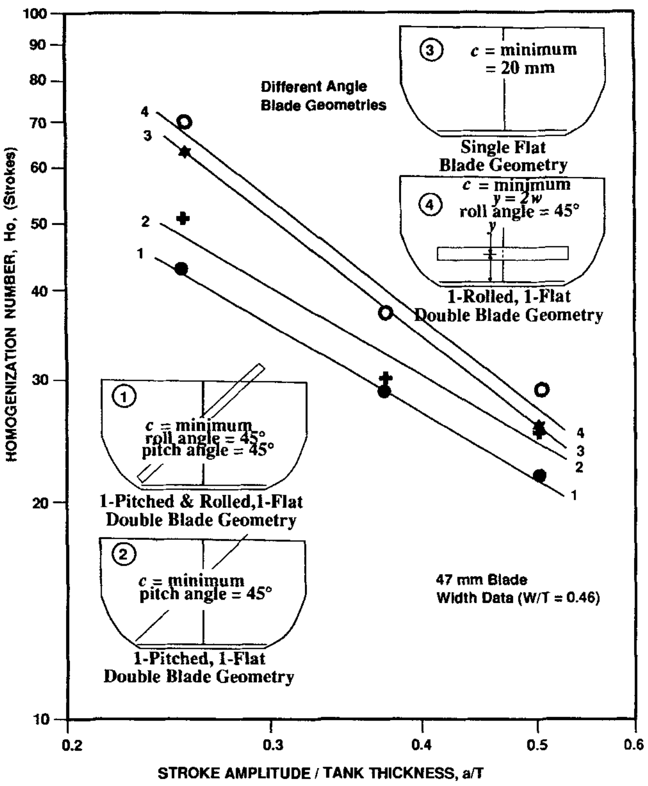

Figure 6. Flat vs. angled blade geometries: blade width = 47 mm, liquid height = 400 mm.

tilting a top horizontal blade led to higher Ho values than a single flat blade geometry, because the second horizontal blade interfered with the bulk circulation.

The bulk circulation of dye in the tank and the homogenization number remained the same at lower liquid depths in other data. Partitions divided the slab tank in half under these conditions, causing compartmentalization. The effect was similar to that reported by Marr and Johnson (1961). At higher liquid depths, an increase in the homogenization number occurred for a given stroke amplitude. Longer circulation paths gave rise to longer mixing times. There was no effect of dye injection location on Ho, a result which is common in cylindrical mixing studies.

Solid suspension

In all cases, the sand was carried upward in the middle of the tank and spread from side to side by the strong bulk circulation in a manner similar to dye mixing. A correlation for the minimum complete suspension frequency, n_s, was obtained as:

$$n_s = 0.314(w/T)^{-0.84}(a/h)^{-0.6}X^{0.10} \quad (4)$$

for $0.46 < w/T < 0.725$, $0.06 < a/h < 0.13$, and $0.7 < X < 20$ from data shown in Figure 7. No data were taken above $w/T = 0.75$, since n_s will increase as w/T approaches one. The correlation is very similar to Eq. 2 cited above, and the effects of geometry on n_s are roughly the same as on Ho. The -0.84 exponent on blade width is similar to the -0.85 exponent on the impeller diameter in the Zwietering correlation. Blade width is the characteristic length of up-down suspension in a slab tank. The exponents on weight fraction are essentially the same.

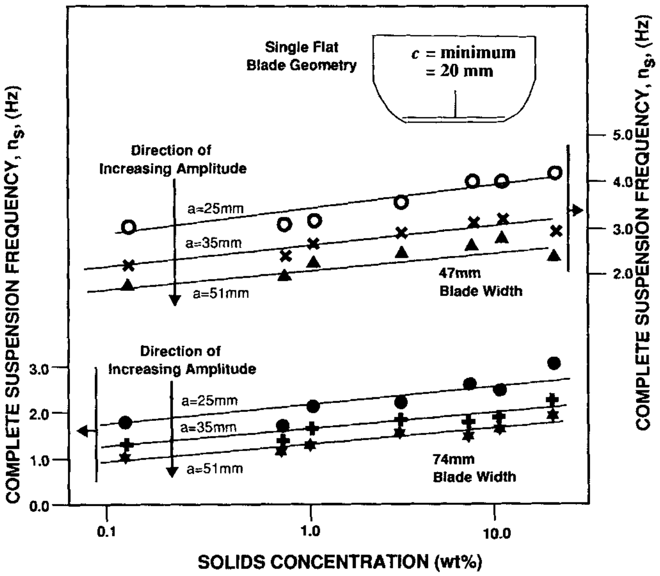

Figure 7. Change in n_s with blade width, amplitude, and solids concentration (wt. %): liquid height = 400 mm, minimum off-bottom clearance, c = 20 mm.

An increase in blade width pulled more fluid upward in its wake, producing higher velocities at the tank bottom. The flow velocity in the wake of the blade increased with increasing stroke amplitude. n_s remained constant or decreased with a decrease in liquid depth.

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Notation

a = amplitude
C = rotary impeller clearance
c = off-bottom blade clearance
D = rotary impeller diameter
d_p = particle diameter
g = gravity
h = liquid height
Ho = homogenization number, stroke or revolutions for mixing
N = impeller rotational speed
n = stroke frequency
n_s = complete off-bottom suspension in up-down and rotary configuration
T = tank thickness or tank diameter
w = blade width
X = weight percent solids
y = blade spacing

Greek letters

$\Delta\rho$ = density difference between solid and liquid
ρ_L = density of liquid
θ = mixing time
ν = kinematic viscosity

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