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**AVOID BLENDING MIX-UPS
AND
CUT REACTION BY-PRODUCTS
BY PROPER FEED BLENDING**

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Avoid Blending Mix-Ups

Achieving uniformity in blending requires an understanding of a number of factors.

The importance of mixing in the chemical process industries is often overlooked. Many causes of process problems, for example, poor conversion and selectivity in large plant reactors and fluctuating composition out of continuous flow blending vessels, can be directly related to inadequate mixing (1). A designer assuming that a continuous reactor is well backmixed or that a plant reactor is blended as rapidly as a small laboratory or pilot-plant reactor could be making a critical error. At times the problem is caused by a lack of data; at other times it's because of a lack of training. Sometimes it's due to scale-up problems. Very few colleges or universities offer a course in mixing, and the only exposure an engineer gets to mixing is typically about a chapter in unit operations. In their defense, our academic colleagues don't have the luxury of exposing the student to as much engineering as they'd like

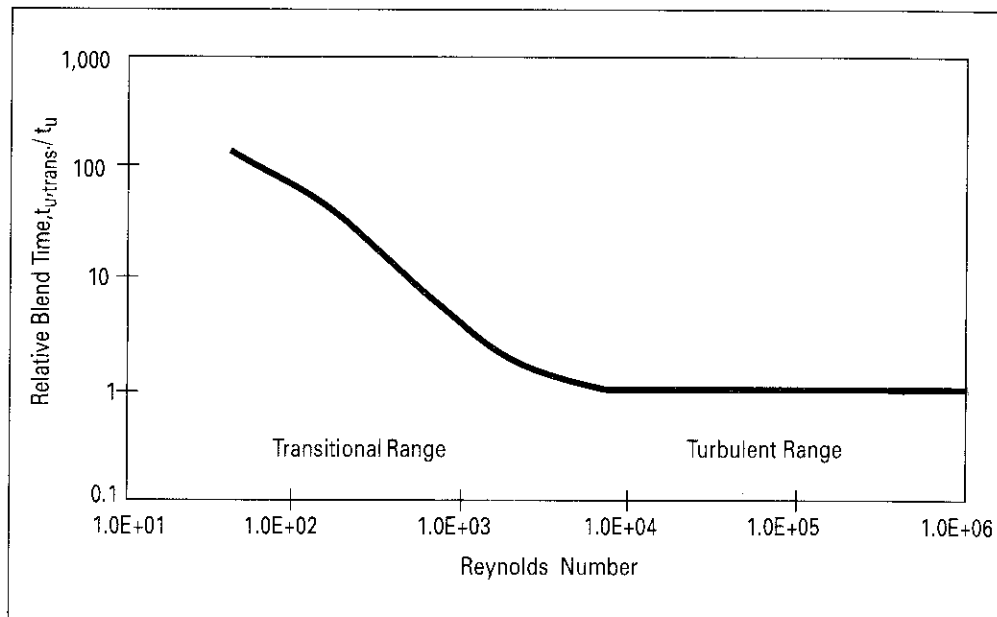
and must often settle for one-week introductions into various areas.

The rate of mixing can influence the time required to reach a given degree of uniformity, or, for batch systems, the reactant or product concentrations at a given time. Equally, for continuous systems, mixing can affect the uniformity of effluent or the reactant or product concentration of the effluent. The following discussions are intended to provide insight to the designer that will guide in determining the role of mixing in a tank or reactor and allow quantitative analysis for certain blending problems.

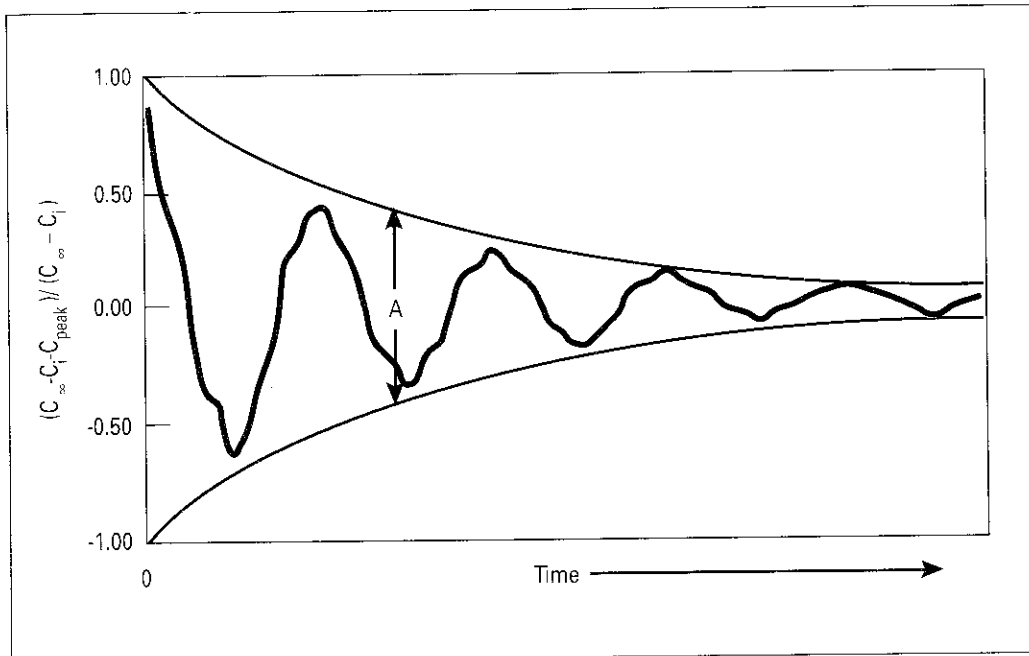
Because most agitators used in the chemical process industries are operated in the turbulent regime, the discussions are primarily restricted to dynamic turbulent mixing.

Turbulent mixing is defined as mixing where the impeller Reynolds number, N_{Re} is greater than or equal to 5,000.

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■ Figure 1. Approximate viscous effects on blend time.



■ Figure 2. Levenspiel-Khang model for mixing uniformity.

$$N_{Re} \geq 5000 \quad (1)$$

The effect of higher liquid viscosities on the relative blend time is shown in Figure 1. When impeller Reynolds numbers fall below 5,000, blend time increases compared to Reynolds numbers greater than 5,000, where the blend time remains essentially constant. This technique for expressing mixing time is only somewhat modified from previous techniques (2,4,6). Figure 1 can provide an approximate indication of how blend time increases below a Reynolds number of 5,000. This relationship is roughly accurate $\pm 30\%$ for most common industrial impellers in the transitional range. Methods will be presented later for calculating the blend time for the dynamic turbulent regime ($Re > 5,000$).

A large number of chemical processes involve Newtonian or near-Newtonian fluids. Therefore, only Newtonian fluids will be discussed, and non-Newtonian fluids will be considered to be outside the scope of this article. Non-Newtonian fluids are often more difficult to process than Newtonian fluids. In handling such fluids, proper expertise should be utilized.

Other restrictions include reasonable impeller-diameter-to-tank-diameter ratios, 0.15 to 0.55, and reasonable liquid-height-to-tank-diameter ratios, 0.5 to 1.5, and will apply only to standard baffled (5), single impeller systems operating at

an elevation of one-third of the tank diameter off bottom.

Vendors and other specialists can often be of great help with problems beyond one's expertise.

The mixing process

Khang and Levenspiel (3) observed that the concentration of material to be blended into a vessel with an agitator behaved as a sinusoidally damped response, Figure 2, and that at any time (t) all possible concentration values would fall within the envelope formed by a pair of oppositely signed exponential curves. Then the maximum concentration variation at time (t) from the

Table 1. Time to achieve 99% uniformity.

Degree of Uniformity	Relative Mix Time
90	0.500
95	0.650
99	1.00
99.9	1.50
99.99	2.00
99.999	2.50
99.9999	3.00

final concentration can be shown to be $\pm A/2$, where $A/2$ can be found from an equation of the form

$$\frac{A}{2} = e^{-kt} \quad (2)$$

where

$$\frac{A}{2} = \left| \frac{C_{\infty} - C_i - C_{\text{peak}}}{C_{\infty} - C_i} \right| \quad (2a)$$

k is the mixing rate constant, time^{-1} , and t is the mixing time.

$A/2$ has been defined here to produce a dimensionless form such that at $t = 0$, $A/2 = 1$ and that at $t = \infty$, $A/2 = 0$. Because $A/2$ can be viewed as the fraction of non-uniformity, the fractional degree of uniformity can then be expressed as

$$U = \left(1 - \frac{A}{2}\right) = 1 - e^{-kt} \quad (3)$$

and the percentage uniformity can be expressed as

$$U \% = \left(1 - \frac{A}{2}\right) \times 100 \quad (4)$$

The time it takes to achieve a given fraction of uniformity can be determined from Eq. 5, a simple rearrangement of Eq. 3:

$$t_U = \frac{-\ln(1 - U)}{k} \quad (5)$$

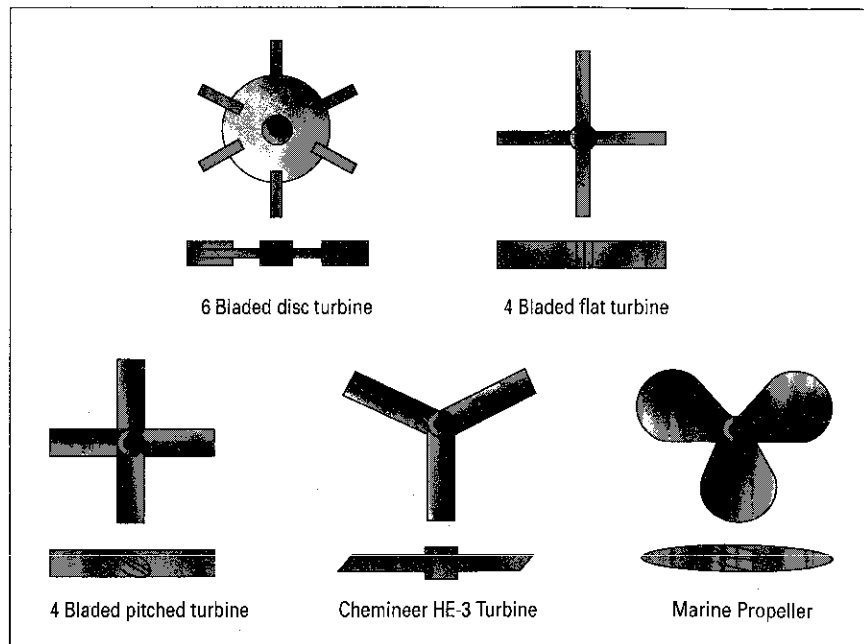
If the time it takes to reach 99% uniformity is defined as t_{99} , then ratios of Eq. 5 will produce

$$t_U = -0.217 \times \ln(1 - U) \times t_{99} \quad (6)$$

where t_U is the time to blend to uniformity U .

This equation can be used to predict the time to blend to a uniformity level other than 99%. Table 1 presents relative time, or the time it takes to achieve a desired level of uniformity compared to the time it takes to achieve 99% uniformity.

Mixing to a uniformity of 90% requires only one-half the time of mixing to 99%, and mixing to a uniformity of 99.9999% requires three times as much mixing time. Industrially, there are processes for



■ Figure 3. Marine propellers are included because they are often the most cost-effective impellers for vessel volumes less than 1000 gallons and for impeller diameters less than 14 inches.

which 90% uniformity is perfectly acceptable, but there are also processes that require much higher levels of uniformity. Determining the required level of uniformity requires careful analysis of the problem and often requires experimental work. The implications of requiring more or less uniformity can easily be determined from Eq. 6.

Determining the mixing rate constant

The dimensionless mixing rate constant in standard baffled tanks, k/N , is a function of Reynolds number and geometry.

$$\frac{k}{N} = f(N_{Re}, \text{geometry}) \quad (7)$$

where,

N_{Re} is the impeller

$$\text{Reynolds number, } \frac{\rho ND^2}{\mu}$$

N = impeller rotational speed, ρ = fluid density, μ = fluid viscosity. The most important geometrical parameters are D/T , T/Z , and impeller type, where D is the impeller diameter, T is the vessel diameter, and Z is the liquid height.

If the impeller Reynolds number

is greater than 5,000, the mixing rate constant is not a function of the impeller Reynolds number. Approximately 80–90% of all agitated chemical processes operate at impeller Reynolds numbers greater than 5,000. Therefore, expressions that do not depend on the Reynolds number can be applied for many agitated chemical process operations. The turbulent mixing rate constant can then be expressed as

$$k = a \times N \left[\frac{D}{T} \right]^b \left[\frac{T}{Z} \right]^{0.5} \quad (8)$$

The constants a and b depend upon the impeller style. Five common impellers styles used for industrial blending operations in vessels are shown in Figure 3. For larger volumes where the impeller diameters equal or exceed 14 in., propellers are not the economical choice. A turbine (HE 3) is often used instead. The constants for these impellers are shown in Table 2.

It should be noted here that the mixing rate constants calculated from Table 2 are based on adding material to the tank on the top surface with axial flow impellers pumping down. Adding reagents just below axial flow impellers should be

avoided because the mixing rate constant decreases, which increases the blend time. It is also worth noting here that the constants for the Chemineer HE-3 impeller may provide significant error if used for other types of high-efficiency impellers. The designer should use care in applying these constants to other high-efficiency impellers.

Determining blend time

Equation 6 relates the blend time for any uniformity level to the time required to reach 99% uniformity, a commonly used design criterion for blending applications; thus, the first step is predicting t_{99} from Eq. 3.

$$t_{99} = \frac{4.605}{k} \quad (9)$$

Substituting for k from Equation 8,

$$t_{99} = \frac{4.605}{a \times N \left[\frac{D}{T} \right]^b \left[\frac{T}{Z} \right]^{0.5}} \quad (10)$$

When sufficiently high fluid viscosities drive the Reynolds number down below 5,000, the blend time will increase. The viscous effects in Figure 1 allow the estimation of blend time for Reynolds numbers less than 5,000 (the last part of example 1 calculates blend time for such a condition). For sufficiently low Reynolds numbers, streamline flow will occur and the blend time, for the nonproximity impellers considered, will be prohibitively long. The impellers described herein are normally not used for Reynolds numbers below 10.

Table 2. Mixing rate constants.

Impeller Type	a	b
Six-Bladed Disk Turbine	1.06	2.17
Four-Bladed Flat Turbine	1.01	2.30
Four-Bladed Pitched Turbine	0.641	2.19
Chemineer HE-3 Turbine	0.272	1.67
Square Pitch Marine Impeller	0.274	1.73

Impeller blending efficiency

The fairest possible comparison of the blending efficiency of two or more impellers is to compare them on the same basic machine loaded to the same horsepower. A basic machine consists of a motor, gear reducer, mounting adaptor, seal (if required), and shaft. With this basis of comparison, the operating costs (related to horsepower) and capital costs (related to machine size) are all essentially constant. For example, this could be done on a 10-hp agitator operating at 84 rpm where the actual shaft horsepower draw from the impeller is 8 hp. One simply needs to size each style of impeller to have an actual shaft horsepower draw of 8 hp. Under fully turbulent conditions, an impeller's diameter is inversely proportional to the power number to the one-fifth power (2):

$$DaN_p^{-1/5} \quad (11)$$

The power numbers for the five impellers discussed previously are shown in Table 3 along with the blade-width-to-impeller-diameter ratio, W/D , selected as well as the

relative impeller sizes based on Eq. 9. Because the power number of highly axial flow impellers will vary somewhat with the impeller-to-tank-diameter ratio, care should be used in extrapolating the power number shown below for the HE-3 and square pitch marine impellers to other impeller-to-tank-diameter ratios.

If the impeller-to-tank-diameter ratio is set for the six-bladed disk impeller at 25% so that all of the above impellers fall within an impeller-to-tank-diameter ratio of 0.15 to 0.55, then the other impeller-to-tank-diameter ratios can be found in Table 4.

Table 4. Impeller-to-tank-diameter ratios.

Impeller Type	D/T
Six-Bladed Disk Turbine	0.250
Four-Bladed Flat Turbine	0.279
Four-Bladed Pitched Turbine	0.327
Chemineer HE-3 Turbine	0.453
Square Pitch Marine Impeller	0.442

By using Eqs. 5 and 8, the ratio of t_U of each of the first three impellers to t_U for the HE-3 impeller can be used to determine the relative blend time for each impeller where the relative blend time for the HE-3 impeller is 1. These relative blend times are shown in Table 5.

The advantages in blending efficiency of a high-efficiency impeller are evident from Table 5. By comparing the different impellers on the basis of equal horsepower and equal speed, one can compare impellers fairly for blending efficiency. Industrial applications often have other criteria that must be satisfied. These other criteria can often be controlling in terms of the most appropriate impeller that should be used, and the designer must often select the most appropriate impeller by considering all process design requirements. The high-efficiency impeller isn't always the best

Table 3. Power numbers, blade-width-to-impeller-diameter ratios, and relative impeller sizes based on Eq. 9.

Impeller Type	N_p	W/D	Relative Diameter
Six-Bladed Disk Turbine	5.00	0.20	0.552
Four-Bladed Flat Turbine	2.88	0.20	0.616
Four-Bladed Pitched Turbine	1.30	0.20	0.722
Chemineer HE-3 Turbine	0.256	Standard	1.000
Square Pitch Marine Impeller	0.289	Standard	0.976

Table 5. Relative blend times.

Impeller Type	Relative Blend Times
Six-Bladed Disk Turbine	1.38
Four-Bladed Flat Turbine	1.35
Four-Bladed Pitched Turbine	1.31
Chemineer HE-3 Turbine	1.00
Square Pitch Marine Impeller	1.08

impeller to use for such processes as liquid-liquid or gas-liquid dispersion, but it is the most cost-effective device for turbulent blending in plant-size process vessels.

Practical blend times

The range of agitators generally applied to a given volume will give about an order-of-magnitude blend

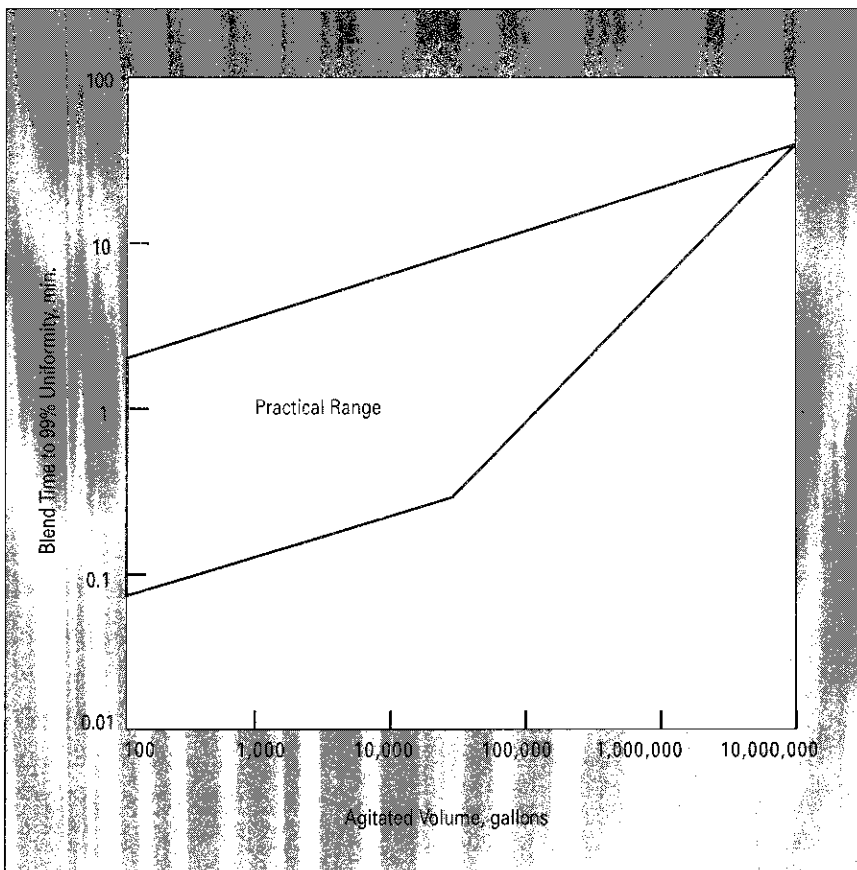
Table 6. Comparison of different agitators.

Horsepower	Speed (rpm)	Machine Size	Torque (in.-lb)
2	45	1	2,300
10	230	1	2,740
20	30	7	42,000
100	155	7	40,700
200	16.5	13	764,000
1,000	84	13	750,000

time variation from the smallest agitator used in that volume to the largest used in that volume, Figure 4 (5); this range is called the practical range in Figure 4. Agitators are the exception; for a given volume they can be made both larger and smaller than covered by this range. From Figure 4 and Figure 5, one can readily see that modestly sized machines will give reasonable blend times even in large tanks.

For example, a 20-hp agitator fitted

with a 45° pitched blade impeller will blend a 100,000 gal vessel in less than 5 min. Thus, for most simple blending applications in the turbulent regime, the costs of providing adequate blending are modest, and the only other important considerations are 1) knowing the blend time and planning sampling and vessel pump-out timing to allow for adequate blending, 2) realizing that high liquid viscosities can dramatically increase blend time, and 3) being aware that fast chemical reactions, especially acid-base neutralizations, often require blend times of a few seconds to minimize undesirable by-product formation. The second article in this series (scheduled to appear in December's *CEP*) will deal with feed blending in chemical reactors. Required blend times that are less than the lower end of the practical range may require custom design. Figure 4 is based on the use of the four-bladed pitched impeller because its performance is somewhat in the center of the range of impellers discussed previously. Blend times for other impeller styles will vary only about ±25%.



■ Figure 4. Practical sizes for agitators in turbulent regimes (for four-bladed pitched turbine).

The horsepower anomaly

Blend times are often associated with horsepower or horsepower per unit volume. Horsepower or horsepower per unit volume is, however, not an effective method of predicting blend time. Six different agitators are shown in Figure 5. These agitators are characterized by horsepower and impeller shaft rotational speed and are provided as a guide as to what particular horsepower and speed combinations can do. Particular attention should be paid to

the fact that horsepower alone is not a very good indicator of blend time performance. Most of an agitator's purchase cost is determined by the torque transmitted to the impeller, and torque is proportional to the ratio of horsepower divided by impeller shaft rotational speed. Agitator machine sizes are based on torque, and three of these basic machine sizes are represented in Figure 5. Both the 2-hp, 45-rpm agitator and the 10-hp, 230-rpm agitator represent the same machine size. The same is true for the 20-hp, 30-rpm agitator and the 100-hp, 155-rpm agitator, as well as the 200-hp, 16.5-rpm agitator and the 1,000-hp, 84 rpm agitator. This comparison is shown in tabular form in Table 6.

Because each of these sets represents a nearly constant torque, one observes that torque is a much better indicator of blend time than horsepower or horsepower per unit volume. Attempts should not be made to predict blend times on the basis of horsepower or horsepower per unit volume. In addition, care should be used in making blending efficiency comparisons solely on the basis of horsepower because it only relates to the operating cost of the agitator, and an accurate comparison should also include the capital cost of the agitator. The practical consequences of this "horsepower anomaly" are that the purchase price of an agitator to handle a blending job will be almost independent of horsepower but the low-speed machine is favored up to the point where the impeller-to-tank-diameter ratio becomes too large because the power requirement—and thus operating cost—decreases as the speed is reduced.

Uniformity in continuous systems

Khang and Levenspiel (3) have revealed that the process of mixing is a first-order rate process. Equation 3 is analogous to an integrated first-order reaction rate equation. This analogy can be extended to continuous mixing systems as well as to multiple-rate processes

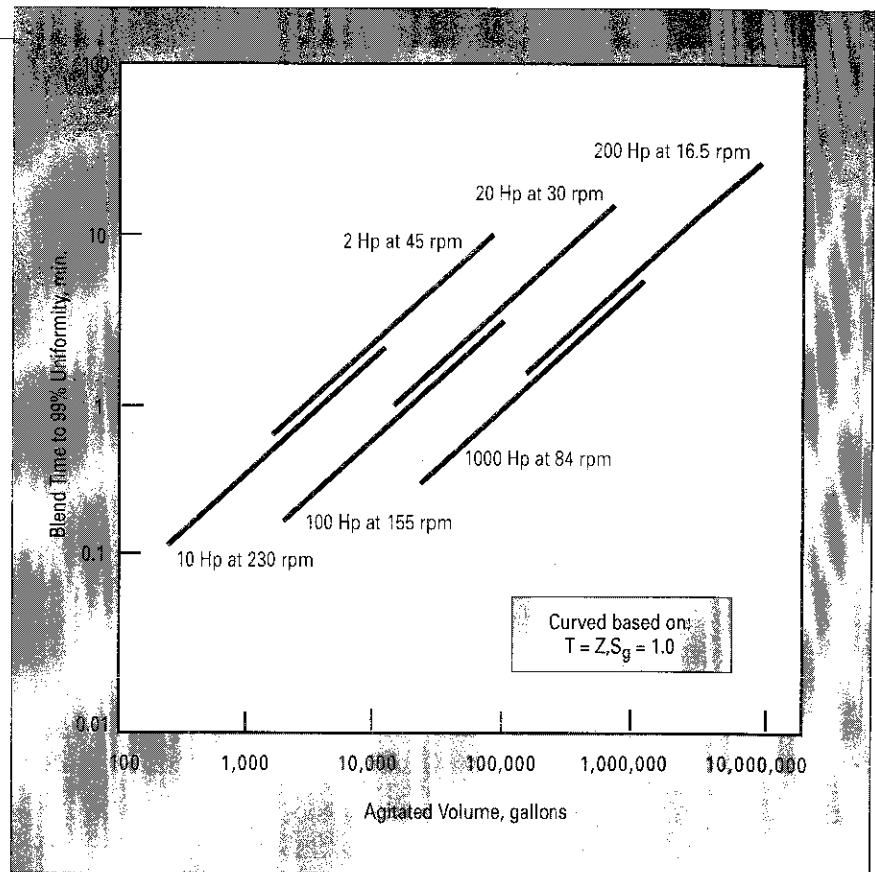


Figure 5. Blend time for various sizes of agitators (for four-bladed pitched turbine).

such as mixing and chemical reactions or mixing, mass transfer, and chemical reactions. The uniformity in a single-stage continuous system, Figures 6 and 7, can be represented by

$$U = \frac{kt_r}{1+kt_r} \quad (12)$$

where the residence time is

$$t_r = \frac{V}{Q} \quad (13)$$

where V is the vessel liquid volume, Q is the volumetric flow rate into the vessel, and the fraction uniformity for a continuous system is given by

$$U = 1 - \frac{(\overline{C_\infty} - \overline{C_{in}} - C_{peak})}{(\overline{C_{out}} - \overline{C_{in}})} \quad (14)$$

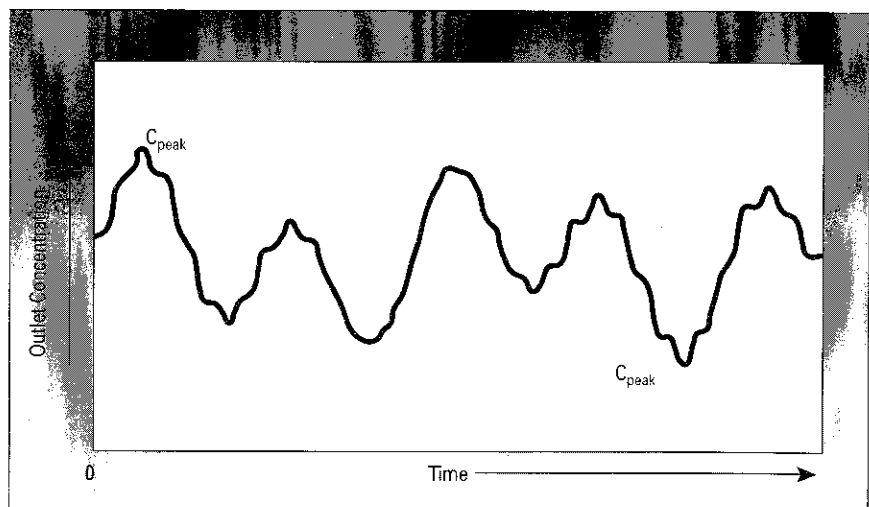


Figure 6. Typical discharge concentration for an agitated continuous stage.

NOMENCLATURE	
C	= constant in Eq. 8.
A	= constant in Eq. 8.
A	= dimensionless
C_{∞}	= time-averaged concentration of blending component as time goes to infinity for batch mixing
C_r	= initial concentration of blending component in tank prior to injection for batch blending.
C_{add}	= bulk mean additive concentration, assumed uniform.
C_{in}	= bulk mean inlet concentration, assumed uniform.
C_{peak}	= maximum or minimum peak concentration in outlet, Figure 6.
C_{out}	= bulk mean outlet concentration
D	= impeller diameter.
j	= number of stages.
k	= mixing rate constant for turbulent flow, time ⁻¹ .
N_i	= impeller rotational speed.
N_p	= power number of impeller, dimensionless, Table 3.
N_{Re}	= impeller Reynolds number, $\rho ND^2/\mu$, dimensionless.
Q_{in}	= volumetric flow rate into vessel.
Q_{out}	= volumetric flow rate out of vessel.
Q_{add}	= volumetric flow rate of additive.
S_g	= specific gravity.
t	= mixing time.
t_r	= residence time.
t_U	= mixing time to percentage uniformity U in turbulent flow.
$t_{0.99}$	= mixing time to 99% uniformity in turbulent flow.
T	= vessel diameter.
U	= fraction uniformity, Eq. 3.
$U\%$	= percent uniformity, Eq. 4.
V	= vessel volume.
W	= impeller blade width.
Z	= liquid height.
ρ	= fluid density.
μ	= fluid viscosity.

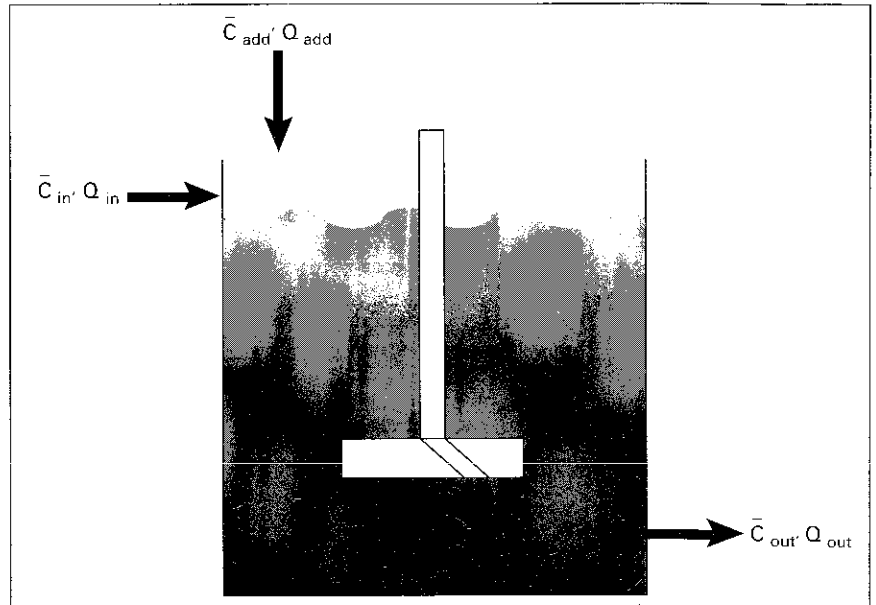


Figure 7. Continuous flow system.

and where C_{out} is the bulk mean outlet concentration

$$\bar{C}_{out} = \bar{C}_{add} \left(\frac{Q_{add}}{Q_{out}} \right) + C_{in} \left(\frac{Q_{in}}{Q_{out}} \right) \quad (15)$$

Refer to the nomenclature for the meaning of terms in Eqs. 14 and 15.

The vessel inlet must be at or near the surface, and discharge flows should ideally be located diagonally opposite the inlet on the bottom.

The first-order reaction analogy can also be extended to equal-volume tanks in series. For a multiple-stage continuous flow system without stage-to-stage backmixing, the uniformity exiting the last stage can be represented by

$$U = 1 - \frac{1}{(1 + kt_r)^j} \quad (16)$$

where j is the number of stages.

Example 1. Given: A batch tank 320 in. in diameter with a flat bottom has a liquid level of 256 in. The tank is to be agitated with a 20-hp agitator operating at 30 rpm utilizing an HE-3 impeller. The

impeller should be sized to draw no more than 16.3 hp. The liquid in the tank has a viscosity of 10 cP and a specific gravity of 1.05. About 1,000 gal of a chemical additive are added to the tank, and it is completely soluble with the tank contents and does not substantially affect the viscosity or specific gravity of the tank contents.

To determine the approximate impeller diameter and the time to blend the tank to 99% uniformity, proceed as follows.

1. The impeller diameter can be calculated from

$$D = hp / (6.55 \times 10^{-14} \times S_g \times N_p \times N^3)^{0.2}$$

where hp is the impeller horsepower draw, D is in inches and N in revolutions per minute.

$$D = 16.3 / (6.55 \times 10^{-14} \times 1.05 \times 0.256 \times 30^3)^{0.2} = 128$$

2. Check the Reynolds Number—it should equal or exceed 5,000.

$$N_{Re} = \frac{10.7 S_g N D^2}{\mu}$$

The constant 10.7 is for N in revolutions per minute, D in inches, and μ in centipoise.

$$N_{Re} = \frac{10.7(1.05)(30)(128)^2}{10}$$

The Reynolds number is greater than 5,000; therefore, the turbulent mixing rate constant provided can be used.

3. The mixing rate constant from Eq. 8 and Table 2 for the HE-3 impeller is:

$$k = 0.272N \left(\frac{D}{T}\right)^{1.67} \left(\frac{T}{Z}\right)^{0.5}$$

where $D/T = 128/320 = 0.400$, $T/Z = 320/256 = 1.25$; Z is the overall height of the liquid. The mixing rate constant is then

$$k = 0.272(30)(0.400)^{1.67}(1.25)^{0.5} = 1.98 \text{ min}^{-1}$$

4. The time to blend to 99% uniformity is given by Eq. 5:

$$t_{99} = \frac{-\ln(1-U)}{k}$$

The mixing time is then

$$t_{99} = \frac{-\ln(1-0.99)}{1.98} = 2.33$$

If the viscosity in this example were 10,000 cP, N_{Re} decreases to 552. From Figure 1, the blend time increases to 18.6 min.

Example 2. Two waste streams are to be blended in a continuous standard baffled 12-ft.-diameter flat bottom tank. The liquid level in the tank is held constant at 18 ft. The primary waste stream is pumped through at a rate of 3,000 gal/min at a pH of 7. The secondary waste stream, pH of 3, is added at a rate of 1,300 gpm. The outlet viscosity is 1 cP, and the outlet specific gravity is 1.02. A 58-in.-diameter four-bladed pitched

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turbine at 30 rpm is operated 4 ft. off bottom.

To determine the peak-to-peak pH variation in the outlet, proceed as follows.

1. Check the Reynolds number:

$$N_{Re} = (10.7)(1.02)(30)(58)^2 = 1 \times 10^6$$

Because this is well into the turbulent range, the mixing rate constant can be determined.

2. The mixing rate constant from Eq. 8 and Table 2 is

$$k = 0.641N \left[\frac{D}{T}\right]^{2.19} \left[\frac{T}{Z}\right]^{0.5} = 2.14 \text{ min}^{-1}$$

where $D/T = 58/144 = 0.403$, $T/Z = 144/216 = 0.667$, and $N = 30$.

3. The residence time from Eq. 13 is $t_r = V/Q = 15,227/4,300 = 3.54$ min, where $V = (12)(2)(\pi/4)(18)(7.48) = 15,227$ gal, and $Q = 3,000 + 1,300 = 4,300$ gal/min.

4. The uniformity from Eq. 12 is

$$U = (2.14)(3.54)/[1 + (2.14)(2.54)] = 0.883.$$

5. Concentrations are converted to $[H^+]$ concentrations by $[H^+] = 10^{-pH}$, where

$$\overline{C}_{in} = 10^{-7}$$

$$\overline{C}_{add} = 10^{-3}$$

and from Eq. 15

$$\overline{C}_{out} = 10^{-3} \left(\frac{1300}{4300}\right) + 10^{-7} \left(\frac{3000}{4300}\right) = 3.02 \times 10^{-4}$$

where $Q_{in} = 3000$ gpm, $Q_{add} = 1300$ gpm, $Q_{out} = 4300$ gpm, and

$$\overline{C}_{out} - \overline{C}_{in} = 3.02 \times 10^{-4} - 1.0 \times 10^{-7} = 3.02 \times 10^{-4}$$

6. With Eq. 14 rearranged, the peak concentration is

$$C_{peak} = \frac{(\overline{C}_{out} - \overline{C}_{in})}{\pm (1-U)(\overline{C}_{out} - \overline{C}_{in})}$$

$$C_{peak} = 3.02 \times 10^{-4} \pm (1-0.883)(3.02 \times 10^{-4})$$

then $(C_{peak})_{high} = 3.38E-4$, $(C_{peak})_{low} = 2.67E-4$, $pH_{low} = 3.47$, and $pH_{high} = 3.57$. **CEP**

J. B. FASANO, technical director, Chemineer, Inc., has 25 years of industrial experience, including PPG Industries and Air Products and Chemicals. He is also adjunct professor of chemical engineering at the Univ. of Dayton (513/454-3200).

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