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Revision Memo

12/01 Minor changes in the text and definitions.



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SCOPE

Described in this subsection are fundamental mixing concepts and various types of equipment commonly used for carrying out mixing operations. Emphasis is placed on mechanical agitators since these have the broadest range of applications. Also included, however, are descriptions of jet, pump, eductor, orifice, and proprietary inline mixing devices. Suitability of these devices for specific mixing duties is also discussed where possible.

Specifying a mixing device is a two-stage process. Mixing needs of the application first have to be quantified and then these needs have to be translated to an equipment design. Included in this base subsection is the translation from mixing need to specified equipment design. General scale-up principles for mechanical agitators are described. The following [Sections XIII-B](#) through [XIII-E](#) cover how to quantify the mixing need for blending of miscible liquids, dispersion of gas in liquid, emulsification of immiscible liquids, suspension of sinking and floating solids. Heat transfer in agitated vessels is covered in [Section XIII-F](#).

REFERENCES

DESIGN PRACTICES

- [Section X](#) Pumps
- [Section XI-L](#) Compressors (Electric Motors)
- [Section XIV](#) Fluid Flow, Perforated Distributor Design

OFFSITES DESIGN PRACTICES

- Section XXII Tank Mixing Guidelines
- Section XXIV Blending Facilities

GLOBAL PRACTICES

- GP 10-9-1 Mechanical Agitators
- GP 10-11-1 Sizing of Drivers and Transmissions

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BACKGROUND

Fluid mixing is one of the most important basic operations of process technology. It is carried out to homogenize fluids in terms of concentration of components, physical properties and temperature; and create dispersions of mutually insoluble phases. It is frequently encountered in the process industry using various physical operations and mass transfer/reaction systems. The fundamental mechanism involves physical movement of material between various parts of the whole mass. This is achieved by transmitting mechanical energy to force the fluid motion.

Mixing systems are broadly divided into single-phase systems involving miscible liquids; and multi-phase systems such as solid-liquid, mutually insoluble liquids, and gas-liquid. These mixing systems offer high flexibility because they can be operated in batch, semi-batch or continuous modes. Adequate mixing is a pre-requisite for the success of chemical processes in terms of minimizing investment and operating costs. In addition, chemical reactions with mass transfer limitation can be enhanced to provide high yields.

The desired mixing in a commercial process is achieved with different types of equipment, e.g., agitators, jets, static mixers, etc. The design approach requires defining process mixing requirements, selecting suitable mixer type, sizing the mixer, specifying tank internals such as baffles, and designing mechanical components such as shaft and drive assembly.

DEFINITIONS

Agitator

A general term used to describe a device which imparts motion to a fluid. Agitator is commonly used as a synonym for the more specific term impeller.

Baffle

Generally a flat plate attached to and perpendicular to the wall of a mixing vessel to alter the fluid circulation pattern and prevent excessive swirl of the fluid in the vessel.

Critical speed

The mixer shaft speed which matches the first lateral natural frequency of the shaft and impeller system. Excessive vibrations and shaft deflections can occur at this speed.

Driver

The motor and gearbox combination used to rotate the agitator shaft.

Draft tube

A centrally located open-ended tube in a mixing vessel which confines the impeller discharge or suction to produce a vertical flow in the vessel.

Geometric similarity

The sizing of the components of a mixing system in such a way that the ratio of linear dimensions of the components (impeller diameter, vessel diameter, vessel height, etc.) remains the same for differing overall system sizes.

Impeller

A physical device which rotates to impart motion to a fluid. Examples are turbines and propellers.

Impeller Reynolds number

A dimensionless number used to characterize the flow regime of a mixing system and which is given in any consistent units by:

$$N_{Re} = \frac{60 \rho N D^2}{\mu} \quad \text{Customary} \qquad N_{Re} = \frac{\rho N D^2}{\mu} \quad \text{Metric}$$

where: ρ = fluid density, lb/ft³ (kg/m³)
 N = impeller rotational speed, rpm (rps)
 D = impeller diameter, ft (m)
 μ = fluid viscosity, lb/ft hr (kg/ms)

♦ The flow is normally laminar for $N_{Re} < 10$, turbulent for $N_{Re} > 10^4$, and transitional in between.



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DEFINITIONS (Cont)

Jet

A fluid stream having a velocity greater than the surrounding fluid which discharged from a nozzle or impeller.

Mixer

- ▶ A device for carrying out a mixing operation and which generally inclusively refers to an impeller, shaft, driver, baffles, and vessel combination.

Power number

A dimensionless number used to describe the power dissipation of an impeller and which with any consistent units is given by:

$$N_p = P / 2.62 \times 10^{-10} \rho N^3 D^5 \quad \text{Customary} \quad N_p = 1000 P / \rho N^3 D^5 \quad \text{Metric}$$

where: P = impeller power dissipation HP (kW)

Propeller pitch

Pitch is the advance of the fluid per revolution on the basis that a propeller is a segment of a screw. Normally "square" pitch is used; i.e., a pitch value equal to the propeller diameter.

Pumping capacity

The amount of discharge flow from an impeller. It is frequently correlated on the basis of the dimensionless impeller pumping number $N_q = Q/ND^3$, where Q = volumetric discharge rate.

Side entering

Describes a mixer design which has a horizontal shaft entering through the side of a mixing vessel.

Solidity ratio

Ratio of projected blade area to the area swept by the impeller.

Standard geometry

Describes a vessel and mixer design based on a fluid depth equal to vessel diameter and a top-entering impeller having a diameter equal to 1/3 of vessel diameter and located with a clearance of 1/3 of vessel diameter above the bottom of the vessel.

Steady bearing

A bearing located at the bottom of the shaft of a top entering impeller to minimize shaft deflection and vibration. It is immersed in the fluid being mixed.

Tip speed

The peripheral speed of an impeller tip which is equal to πND .

Top entering

Describes a mixer design which has a vertical shaft entering through the top of a mixing vessel.



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EQUIPMENT TYPES AND APPLICATIONS

The commonly used types of mixing equipment can be placed in the broad categories: (1) mechanical agitators, (2) inline motionless mixers, and (3) tank jet mixers. The nature and type of agitator used depends upon the scale and type of mixing and upon the fluids being mixed. **Table 1** provides a general basis for selection of impeller type and other mixing equipment.

MECHANICAL AGITATORS

- Agitated tanks are equipped with a single or multiple impellers attached to a shaft which is rotated by a motor/gear box drive. A standard geometry of a top entering agitated tank is shown in **Figure 1**. There are literally hundreds of impeller types in commercial use, only the most common and general types are shown in **Figure 2**. Their classification is based on shear level and flow patterns. Turbines provide high shear levels while close-clearance impellers (**Figure 2D**) such as anchors and helical ribbons produce low shear. Turbines are further classified based on flow direction as axial flow (**Figure 2A**) and radial flow (**Figure 2B**) impellers. Recent developments in the impeller technology have been focused on increasing axial flow at reduced shear. These impellers use hydrofoil profile of blades for efficient and more streamlined pumping (**Figure 2C**). Turbine impellers have the widest use in low and medium viscosity liquid applications, solids suspension, liquid dispersion, and gas-liquid contacting.

The oldest axial flow impeller design is the marine propeller which is used as a side-entering mixer in large tanks and top entering in small tanks. Top-entering mixers also use pitched blade turbine (PBT) for axial flow (**Figure 3B**) and disk flat blade turbine (FBT) for radial flow (**Figure 3A**). Some hydrofoil impellers, such as Lightnin A315 and Prochem Maxflo, are designed with high solidity ratio for gas dispersion and blending of non-Newtonian liquids. Radial flow impellers provide higher shear and lower discharge flow compared to axial flow impellers. DFBT and Chemineer CD6 impellers are efficient for gas dispersion applications.

INLINE MOTIONLESS MIXERS

Inline motionless mixers derive the fluid motion or energy dissipation needed for mixing from the flowing fluid itself. These mixers include:

Orifice Mixing Column - An orifice-mixing column consists of a series of orifice plates contained in a pipe. The pipe normally is fabricated of two vertical legs connected by a return bend at the bottom with the orifice plates installed between flanges in the vertical legs. Typical use is for cocurrent contacting in caustic and water washing operations. It is generally designed at mixing energy of 1100 to 4400 ft-lbs/ft³ (50 to 200 kJ/m³) and contact times of 10 to 50 seconds. Typical pressure drop per orifice is in the range of 1 to 3 psi (7 to 20 kPa).

Mixing Valve - This type of mixing device is normally a manually operated globe valve operated at 3 to 50 psi (20 to 340 kPa) pressure drop. Common use is for water and crude oil mixing before a desalter and in caustic scrubbing operations.

Static Mixers - These motionless mixers consist of repeated structures called mixing elements attached inside a pipe. These mixing elements alternately divide and recombine fluids passing through. As a result, they create shearing action at a cost of pressure drop. Static mixers provide complete transverse uniformity and minimize longitudinal mixing, therefore, their performance approaches perfect plug flow conditions. There are many proprietary designs marketed, but only a few are shown in **Figure 4**. These mixers are used for continuous in-line blending and for cocurrent contacting operations.

TANK JET MIXERS

As an alternate to mechanical agitators, storage and blending tanks can be agitated by jet mixers. Jet mixers can be used for continuously blending miscible liquids as they enter a tank or batchwise by recirculating a portion of the tank contents through the jet. They are commonly used to prevent stratification in product and intermediate tankage.

The jet mixer is a streamlined nozzle installed in the side of a tank near the bottom. It points diametrically across the tank and discharges at an angle above the horizontal. A typical jet nozzle design is shown in **Figure 5**. A jet eductor, shown in **Figure 6**, is sometimes used for higher entrainment of the surrounding liquid.

BASIC DESIGN CONSIDERATIONS

(1) MECHANICAL AGITATORS

TANK GEOMETRY

For large (> 30 ft or 9 m diameter) storage and blending tanks, a side entering propeller agitator is normally used. The agitator shaft is set at an angle to a tank diameter as shown in **Figure 7**. No tank baffles are used. For very large (> 120 ft or 36 m diameter) storage tanks having high mixing power requirements, multiple mixers can be used. Details concerning mixer design for miscible liquid blending are given in [Section XIII-B](#).

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BASIC DESIGN CONSIDERATIONS (Cont)

- Most mechanically agitated mixing operations normally use vertical mixer shafts in vessels equipped with wall baffles. Unless process requirements dictate otherwise, "standard" tank geometry illustrated in **Figure 1** is used. Standard geometry utilizes only one impeller on the mixer shaft. If an application such as gas absorption requires that the fluid depth, Z, be greater than 1.2 times tank diameter, T, an additional impeller spaced at least an agitator diameter, D, above the standard bottom agitator should be used. Standard geometry normally implies a top-entering shaft. However, from a flow pattern and power dissipation standpoint, a bottom-entering shaft is equivalent. If shaft seal problems are handleable, bottom entry can reduce the required shaft length in vessels which are designed with tall vapor spaces for foam disengagement, etc.

PUMPING, VELOCITY HEAD AND POWER

Mechanical mixers can be compared with pumps because they produce circulating capacity Q and velocity head H. Q in a mixing tank represents internal recirculation and can be calculated by:

$$Q = N_q N D^3 \quad \text{Eq. (1)}$$

where: Q = pumping rate, ft³/min (m³/s)
 N_q = pumping number, dimensionless - depends on impeller type and N_{Re}
N = impeller rotational speed, rpm (rps)
D = impeller diameter, ft (m)

The velocity head H from kinetic energy generates shear through the pulsating motion of the fluid and is proportional to square of impeller tip speed (ND).

$$H \propto (ND)^2$$

The power consumed by a mixer can be obtained by multiplying Q and H and is given by

$$P = 2.62 \times 10^{-10} \times N_p \rho N^3 D^5 \quad P = N_p \rho N^3 D^5 / 1000 \quad \text{Eq. (2)}$$

where: P = mixer power, HP (kW)
 N_p = power number, dimensionless - depends on impeller type and N_{Re}

- Figure 8** shows the relationship between N_q and N_{Re} for a 45 pitched blade turbine (PBT) with various impeller to tank diameter ratios. For propellers operating at $N_{Re} > 3000$, N_q can be assumed to be 0.5. **Figure 9** shows relationship between N_p and N_{Re} for seven commonly used impellers. Similar plots for propellers with different pitch are given in **Figure 10**.

Values of the N_p and N_q under turbulent flow conditions for some of the hydrofoil impellers are given in **Table 5**.

The power numbers given in **Figures 9** and **10** apply to the impeller types indicated and specifically when these impellers are employed in a tank of standard geometry which includes wall baffles (except Curve 7 of **Figure 9** specifically applies for the finger baffles shown). For side-entering propeller agitators which are offset from or set at an angle to a tank diameter, **Figure 10** is still applicable. For mixing liquids having viscosities greater than 5000 centipoises, baffles can also be eliminated in other vessels without altering the power number relationship.

Impeller power dissipation can be estimated for a number of departures from the standard geometries. For turbine blade width / diameter ratios other than shown in **Figure 9**, power number can be calculated as being proportional to this ratio. For installations having multiple impellers on the same shaft, the power dissipation is a function of impeller spacing as shown in **Figure 11** for turbines and **Figure 12** for propellers. Changes in baffle width from the standard T/12 to T/10 affect power number as shown in **Figure 13**. The sparging of a gas into a mixing vessel reduces power dissipation as indicated in **Figure 14**. **Figures 11** through **14** give the ratio of power number for the non-standard geometry (or gas sparging situation) to the power number for standard geometry (or no gas flow). Thus, the power number for the non-standard situation is the product of the appropriate standard value times the ratios from the figures.

- The power rating of the driver for the impeller has to exceed the power dissipation to the fluid because of driver, seal, and bearing losses. Unless specific data are available, these losses can be estimated as 20% of the calculated dissipation. This 20% also provides a safety allowance for uncertainties in the correlations and fluid properties used in calculating the dissipation to the fluid. For specification this power is rounded up to one of the available standard electric motor sizes listed in **Table 3**.

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BASIC DESIGN CONSIDERATIONS (Cont)

NON-NEWTONIAN FLUIDS

The power dissipation correlations discussed above are specifically applicable to the mixing of fluids having Newtonian viscosity behavior. A Newtonian fluid has a viscosity independent of the shear to which the fluid is subjected. Thus, although the shear rates vary greatly throughout the fluid in an agitated vessel, the viscosity of a Newtonian fluid will be the same at all points in the vessel. In contrast, the apparent viscosity of a non-Newtonian fluid at any point in the vessel depends on the magnitude of either the shear stress or the shear rate at that point and may also depend upon the previous history of the fluid. If the apparent viscosity decreases with increasing shear rate, the fluid is called pseudoplastic. If the apparent viscosity increases with shear rate, the fluid is termed dilatant. If the apparent viscosity of a pseudoplastic fluid decreases with the time a particular rate of shear is applied, the fluid is termed thixotropic.

The Newtonian/non-Newtonian behavior of a fluid or fluid mixture is known only from prior experience or by viscometry. Most non-Newtonian fluids encountered are pseudoplastic. For these fluids, studies have established that the power number versus impeller Reynolds number behavior is such that the power number is always equal to or less than the value for a Newtonian fluid. Thus, for pseudoplastic fluids, **Figures 9 and 10** can still be used and will be conservative. If the agitation conditions are known to be turbulent and result in operation on the flat portion of the power number-Reynolds number curve, a precise knowledge of apparent viscosity is not needed. However, in the laminar range, a knowledge of average shear and thus apparent viscosity is needed to calculate the appropriate Reynolds number. In a stirred tank the average shear rate is equal to approximately 10 times the rotational speed of the impeller. Experimental measurements are required to determine apparent viscosities at this shear rate. Chapter 10 of the Holland and Chapman reference or EMRE's Chemical Engineering Technology (CET) section should be consulted.

STANDARD DRIVER SIZES

- Drivers for mixers are produced with gear reducers having standard output shaft speeds and powered by electric motors having standard horsepower ratings. The standard output speeds of the American Gear Manufacturers Association (AGMA) are given in **Table 2**. For side-entering and portable propeller agitators, the 280, 350, and 420 rpm speeds are the only ones in general use. Most vendors of mixer drivers provide gearboxes which make possible the changing of gears to produce other standard output speeds. However, making such changes requires consideration of the horsepower rating of the motor, the torque rating and service factor of the gearbox and motor, and the critical speed of the shaft and impeller assembly. The mixer vendor or CET section should be consulted.

Standard motor horsepower ratings are given in **Table 3**.

INVESTMENT AND OPERATING CONSIDERATIONS

In selecting among mixing system designs, both investment and operating costs must be considered. With turbine agitators, process requirements can frequently be satisfied by mixers having different horsepower and speed combinations. Because of the high cost of gear speed reducers, a higher horsepower-higher speed unit will sometimes cost less than a lower horsepower-lower speed unit. In many continuous operations, the lower cost of the higher horsepower unit is negated by the higher power costs.

SCALING-UP FROM LABORATORY AND PILOT PLANT STUDIES

The main objective of scale-up is to achieve the same quality of mixing in a commercial size mixing tank as in a laboratory test tank. Unfortunately, it is not possible to maintain the same combination of flow and shear distributions in commercial mixers as in small-scale tanks. Several scale-up methods have been developed depending on the process type and mixing requirements, but all methods emphasize geometric similarity. Geometric similarity refers to maintaining the same impeller type; and relative dimensions of impeller, liquid height and baffles.

The most commonly used scale-up criterion uses constant P / V , which is usually conservative. Depending on the process requirement, P / V should be increased or decreased (**Figure 15**) with increase in volume according to $P / V = \text{constant} (V^y)$. The scale-up exponent 'y' can be negative or positive and should be determined either through pilot plant testing or from recommended values in **Figure 15**.

(2) IN-LINE MOTIONLESS MIXERS

These mixers are generally suitable for continuous mixing operations where low and high viscosity miscible liquids are blended, immiscible liquids are contacted, or gas is dispersed in a liquid. These mixers are inexpensive when short mixing time is acceptable and the system is not limited by pressure drop. Detailed design considerations for in-line mixers are discussed in the subsequent subsections on individual application types.

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BASIC DESIGN CONSIDERATIONS (Cont)

(3) JET MIXERS

These mixers are commonly used in product blending and storage tanks equipped with a pumparound system with sufficient pumping capacity and head. They may be preferred to side-entering propellers because of their lower cost and lower maintenance requirements, and possibly lower cost if a suitable pump is available.

DESIGN PROCEDURE

MECHANICAL AGITATORS

Set Vessel Geometry - For large storage and blending tanks which use side-entering propeller agitators, the vessel geometry is set by process needs rather than mixing considerations. The mixer design is adapted to a tank of specified geometry and is discussed in [Section XIII-B](#).

For vessels to be mixed with top-entering agitators, "standard geometry" ([Figure 1](#)) should normally be used. Vessel diameter, T, can be estimated from:

$$T = \left[\frac{4}{\pi} V \right]^{1/3} \quad \text{Eq. (3)}$$

where V is the maximum fluid volume to be mixed in the vessel. This diameter is then rounded to the nearest larger standard drum and head diameter. Liquid depth in the vessel can then be calculated. Depth and volume in the bottom head are included. The head can be any of the standard types available for the pressure rating of the vessel. Vessel volume above the fluid must be added in many installations to provide for the increase in liquid volume due to gas holdup during sparging or to accommodate foaming. In all cases, space is left between the top of the liquid and the top of the vessel, thus the liquid has a free interface. Normally for vessels with top-dished heads, the space above the upper tangent line is left unfilled. With flat heads or open tops, the vertical space left unfilled should be at least 1/10 of vessel diameter.

For mixing fluids having viscosities less than 5000 cP, 4 full length wall baffles spaced 90 apart are used. In vessels having dished heads, the baffles are only used on the straight side. Except when mixing buoyant particle slurries, baffle width is set at 1/10 to 1/12 of vessel diameter. For buoyant solids, baffle width is reduced to 1/50 of vessel diameter. The baffles are set out from the vessel wall by 1/72 of vessel diameter, especially when solids are present. If the fluids in the vessel will always have a viscosity greater than 5000 cP, wall baffles should be narrower than conventional baffles. For very high viscosity liquids, wall baffles may not be needed.

Pick Impeller Type and Approximate Diameter - Impeller type should be selected in accordance with the discussion in **EQUIPMENT TYPES AND APPLICATIONS**. [Table 1](#) in particular provides specific guidance. For mixing fluids having viscosities up to 1000 cP, impeller diameter is set at approximately 1/3 of vessel diameter. As fluid viscosity increases to 10,000 cP, impeller diameter should be increased to approximately 1/2 of vessel diameter. Except for close proximity agitators, agitator diameter should not exceed 0.7 times vessel diameter for any viscosity. Except for very small impellers, impeller diameters are specified in the nearest whole inch or 25 mm increments.

Calculate Impeller Speed and Exact Diameter - For the set vessel geometry and approximate impeller diameter, impeller speed is then calculated to satisfy the stated process requirements.

1. **For process requirement stated as a tip speed**, impeller speed is given by:

$$N = \left[\frac{\text{tip speed}}{\pi D} \right] \quad \text{Eq. (4)}$$

For tip speed in ft/min (m/s),

where: D = impeller diameter, ft (m)
N = impeller speed, rpm (rps)