MIXING FOR THE PROCESS INDUSTRIES

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Preface

This book is written primarily for an audience of engineers who design, specify, procure, update, and maintain mixers in the processing industries. It is an application-oriented handbook to support the design and operation of mixers for liquids, liquids and solids, liquids and gases, and any combination thereof. This book does not address solids mixing.

Mixing applications are identified as either flow controlling or shear rate controlling, and are addressed as such. Specific mixing applications and design parameters are presented for blending, solid suspension, heat transfer, mass transfer, dispersions, extractions, etc.

Fundamentals of mixer design and operation, agitation applications spectrum, types and geometries of mixing impellers, etc. are presented in Chapter 1, providing the basis for practical information presented in subsequent chapters.

Flow controlled mixing applications are discussed in Chapter 2. These include blending, solid suspension, heat transfer, dissolving of solids, and crystallization. Optimization of mixer design is emphasized, with an eye to saving power and capital cost. Also discussed is the use of draft tube circulator mixers to optimize mixer performance and cost.

Shear controlled mixing applications are addressed in Chapter 3. These include gas-liquid dispersions, mass transfer, fermentation, emulsions, extractions, and dispersions of solids in liquids.

Chapter 4 focuses on geometric and nongeometric scaleup of mixers to accomplish equal or better mixing results in various scales of volume. Scaleup relevant to applications of blending, solids suspension, and mass and heat transfer is explained.

Chapter 5 is devoted entirely to static pipeline mixing. A step-by-step approach to design of static mixers is offered.

Retrofitting of agitators is presented in Chapter 6 as a cost-effective alternative to purchasing and installing a new mixer. Retrofitting of impellers is discussed from the perspective of improving mixing results at similar power levels and obtaining similar mixing results at reduced power levels.

These early chapters emphasize process-results aspects of mixer design and operation. Chapter 7 introduces mechanical design considerations for agitator design, operation and maintenance. Mixer shaft, impeller, and drive mechanical design parameters and contraints are explored. Chapter 7 also surveys the various types of commercially available mixer shaft seals and drive assemblies.

Formulae and their practical use in example calculations are found in every chapter to help the reader work through a design scenario or solve a mixing problem.

Mixing for the Process Industries will be a tool to design new mixers or revise existing agitators for optimum performance in a given application. It will enable the reader to solve operational problems, enhance mixing process results, and ensure mechanical reliability and integrity of agitators. Finally, it will provide a means to optimize mixer design and selection from an applications perspective, tried and proven in industrial processing situations.

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Fundamentals of Mixing

A. INTRODUCTION

In the design and operation of a full-scale plant, agitation equipment often plays a major role in optimization of the overall process. To meet the overall process objectives, it is essential to determine the significant mixing parameter(s) and incorporate that knowledge into a successful commercial-scale design. Economic benefits, such as minimum power usage or low capital cost, can be achieved by applying technology in a manner that assures the specific process in mind is optimized with respect to agitation, and that the ultimate mixer selection is an optimum design.

The effect that agitation has on process results is established by evaluating the following:

1. Process Design Requirements
2. Mixer Impeller Flow and Shear Development
3. Agitator Mechanical Design Considerations
4. Vessel and Mixer Support Structural Requirements

Power consumption by a mixer with a particular impeller geometry, in a specific process and vessel environment, bears no relationship to achieving a desired process result. Flow and shear generated by mixer impellers, within a specific vessel constraint, achieve desired results for the process or application at hand. The proper balance of flow and shear development, in concert with a mixer turbine design and selection that provides this proper balance with minimum power requirement, assures an optimum agitator design. As one might expect, there is a wide spectrum of flow and shear characteristics available from a number of possible impeller or turbine configurations that must be tailored to a specific process result and mixing requirement.

Well established mixing technology can be applied to agitator design and selection for many processes such as blending, heat transfer and solids suspension. An expansion of this basic technology is required for applications involving specific mass transfer needs and many complex reactor systems. In some cases, pilot plant testwork must be pursued to develop data for process optimization, mixer scaleup criteria, and optimum mixer design and selection.

Fluid mixing can be a simple process, with every aspect of mixer performance easily evaluated. It can also be extremely complex, with many independent steps involving a variety of fluid phenomena.

Mixer performance is typically expressed in terms of bulk fluid velocity generated, shear rate, total pumping capacity of the impeller, total flow in the vessel, or in terms of a desired process mixing result (i.e., blend time, solids suspension regime, etc.).

If the application is relatively simple to evaluate, a thorough examination of complicated fluid mechanics in a mixing tank will not be necessary. If the process is complex, however, a complete investigation of fluid shear rates and stresses, flow rate, turbulence, and their effects on mixing results may be required. Such a procedure is best carried out in a controlled pilot plant test program.

It may be possible to express a complex mixing process in terms of only one, or a few, simple velocity and pumping capacity relationships. If such were the controlling factors in the process, the design of an appropriate mixing system would be straightforward.

Problems can often arise in clearly differentiating between processes to which comparatively simple physical and visual concepts can be applied and those for which more elaborate qualitative and quantitative aspects must be explored.

For example, consider a mixing process that requires the suspension of solids in a liquid, in which a chemical reaction takes place between components of the liquid and solid phases. If the process engineer decides that the reaction kinetics occur when a certain degree of solids suspension has been achieved, the engineer should issue process specifications calling only for a specific degree of solids suspension.

If the mixing system so specified accomplishes the desired process result, the agitator design will be acceptable. The opposite will be seen, however, if the observed relationship between the specified suspension of solids in the tank and completion of reaction is not as anticipated.

B. FLUID MECHANICS—FLOW AND SHEAR

Impeller type mixers are essentially pumps (albeit not very efficient ones), having many of the same characteristics.

The most fundamental of these is that the mixer impeller power consumption is proportional to its flow and head development:

$$P \propto QH \tag{1}$$

where: P = power
Q = flow rate
H = head.

All the power supplied from the agitator to the fluid produces flow, velocity head, or shear.

Unlike a pump casing, however, a mixing tank is not a confining channel. Therefore, the measurement and calculation of turbine flow and head is not as quantitative as is the case of a pump and piping system. Axial flow mixer impellers operating in a draft tube at close clearance to the tube walls simulate an axial flow pump in its casing. In this system, flow and head development are quantitative, and the efficiency in producing same per expended unit of power consumption is increased over that in a mixing tank without draft tube. Usually, impeller flow is expressed as the pumping capacity normal to the discharge plane of a turbine.

The discharge area of a typical constant pitch axial flow turbine is a conical surface, because the flow has both axial and radial components. The flow from streamlined airfoil impellers of variable blade pitch tends to be more completely axial, so its discharge plane approximates a horizontal disk surface. An impeller in a tank emits a jet stream. This stream has a certain velocity, flow and cross-sectional area. As the jet expands within the confines of the tank, the area, flow, and velocity change markedly and additional fluid is entrained. Fluid momentum, however, is conserved. The momentum of the stream leaving the impeller equals the momentum of fluid in the expanded jet. The momentum of the impeller, which manifests itself as velocity of motion in the tank, is a measurement of mixing or process result.

Impeller flow refers only to the flow directly produced by the impeller. There is also entrained flow, which is that fluid set into motion by the turbulence of the impeller stream. Entrained flow is often a major portion of the total flow, as illustrated in Fig. 1-1.

Equation (1) may be expressed in terms of impeller rotational speed N and impeller diameter D as follows:

$$P \propto N^3D^5 \quad \text{for turbulent flow regimes} \tag{2}$$

$$P \propto N^2D^3 \quad \text{for laminer flow regimes} \tag{3}$$

Other important relationships are:

$$Q \propto ND^3 \tag{4}$$

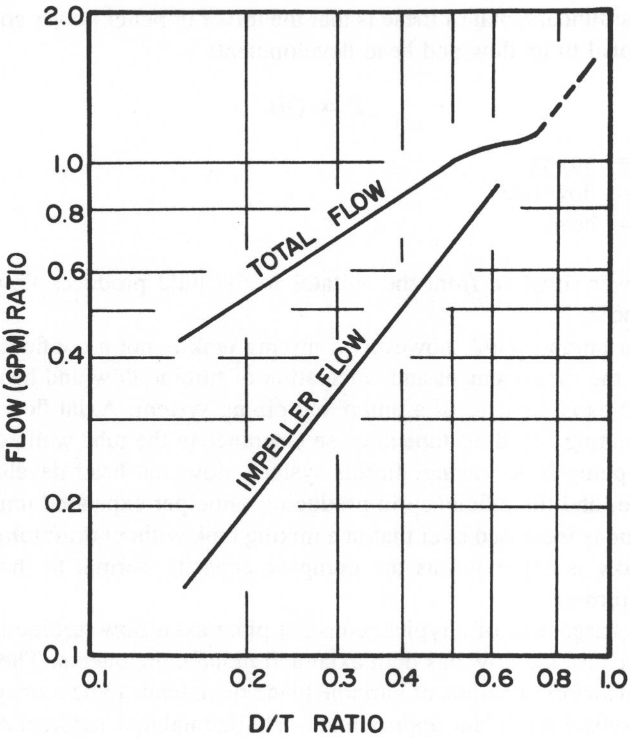

FIGURE 1-1. Total flow versus impeller flow. (*Mixing Equipment, Inc.*)

$$H \propto (ND)^2 \tag{5}$$

$$Q_p \propto D^{4/3} \tag{6}$$

$$N_p \propto D^{-5/3} \tag{7}$$

Equations (6) and (7) are derived from Eq. (1) and express Q and N at constant power (denoted by subscript p) in terms of D. As impeller diameter increases, the impeller flow increases and the speed decreases rapidly at constant power. It follows from Eq. (6) that mixing or process results predicated on flow (i.e., flow controlled applications) can be improved at constant power by using a larger diameter impeller running at a slower speed.

Another consideration is the affect that a larger diameter impeller operating at reduced speed and at constant power has on torque. Torque is related to power P and speed N as follows:

$$\text{Torque} \propto P/N \tag{8}$$

As diameter increases and speed decreases at constant power to obtain greater flow-controlled process results, the torque rises rapidly:

$$\text{Torque}_p \propto D^{5/3} \tag{9}$$

As shown in Fig. 1-2, there are numerous combinations of power and torque accomplishing the same mixing results for flow controlled applications. The question remains as to which selection is optimum for you?

The answer lies in economics. In buying an agitator, both capital cost (i.e., purchase price of the machine) and operating cost (i.e., power requirement) must be taken into account. It must be remembered that

$$\text{Capital Cost} \propto \text{Torque} \tag{10}$$

$$\text{Operating Cost} \propto \text{Power} \tag{11}$$

Your economic situation will dictate which selection is right for you. Inevitably the tradeoff between higher capital cost for lower operating cost or vice versa must be evaluated to select the optimum agitator.

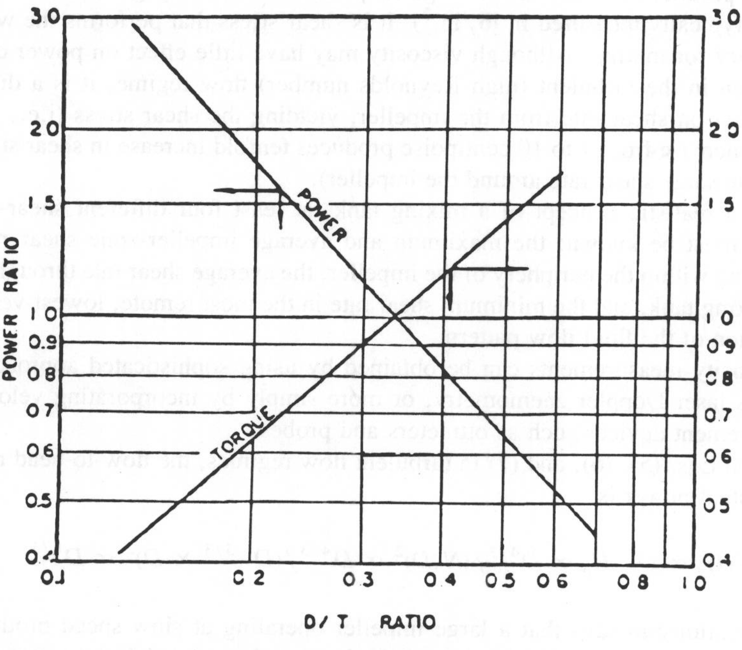

FIGURE 1-2. Power–torque relationship for constant process results at constant power input. (*Mixing Equipment, Inc.*)

A rotating mixer impeller will produce a flow velocity profile along the length of impeller blade. The profile may be nearly uniform or variable from point to point along the blade. The profile consists of velocity vectors with magnitude and direction. The direction will be predominantly axial or radial (i.e., parallel or perpendicular to the axis of rotation) depending on the impeller geometry. There is a center of rotation about which all the flow can be considered to pass.

When the flow is turbulent, velocity fluctuations are significant. These can be analyzed mathematically to give one value of average velocity at a given point in a stirred tank. When the flow is laminar, fluctuating velocity components are not present. In qualitative terms, the shear rate between adjacent layers of fluid, based on average velocity at any profile point, is used to develop the concept of macroscale shear rate. The shear operates on particles that are too large to respond to the high-speed velocity fluctuations.

Using either average velocity in turbulent flow or actual velocity in laminar flow, a velocity profile may be established for a particular impeller geometry of given diameter and speed. Measuring the slope of the velocity gradient along the blade length gives the shear rate, in reciprocal seconds, at any point on the profile. The maximum shear rate and average shear rate around the impeller can be calculated.

The product of shear rate at a given point and viscosity gives fluid shear stress (typically measured in $lb/in.^2$). It is shear stress that performs the work necessary for mixing. Although viscosity may have little effect on power consumption in the turbulent (high Reynolds number) flow regime, it is a direct multiplier on shear rate from the impeller, yielding the shear stress (i.e., viscosity increase from 1 to 10 centipoise produces tenfold increase in shear stress from the same shear rate around the impeller).

For a realistic concept of a mixing tank, at least four different shear-rate values must be known: the maximum and average impeller-zone shear rates occurring within the periphery of the impeller, the average shear rate throughout the mixing tank, and the minimum shear rate in the most remote, lowest-velocity region of the fluid flow pattern.

Velocity measurements can be obtained by using sophisticated approaches such as laser Doppler anemometry, or more simply by incorporating velocity measurement devices such as ottmeters and probes.

From Eqs. (5), (6), and (7) in turbulent flow regimes, the flow-to-head ratio at constant power is

$$(Q/H)_p \propto Q_p/H_p \propto D^{4/3}/(N_pD)^2 \propto D^{4/3}/(D^{-5/3} \times D)^2 \propto D^{8/3} \quad (12)$$

This relationship says that a large impeller operating at slow speed produces high flow and low impeller head. Impeller head, being related to the square root of fluid shear rate, is a measure of the flow-to-fluid shear rate around the impeller. Hence it follows that a small impeller turning at high speed develops a high shear rate and low pumping capacity. Every mixing application has an optimum balance of flow and fluid shear.

For a given impeller geometry, *maximum* shear rate is proportional to impeller tip speed:

$$\textit{Maximum}\text{ Shear Rate} \propto \pi DN \tag{13}$$

whereas *average* shear rate is proportional to speed:

$$\textit{Average}\text{ Shear Rate} \propto N \tag{14}$$

Fluid discharge from an impeller can be measured with a device that has a high-frequency response, allowing velocity to be determined as a function of time. At any point in time, the fluid velocity can be expressed as an average velocity plus some fluctuating velocity component. Integration of the average velocities across the discharge of the impeller allows for the calculation of the impeller or primary pumping capacity normal to the discharge plane. This plane is bounded by the impeller blade diameter and height.

Velocity gradients between the average velocities operate only on larger particles (typically greater than 1,000 micron in size). This phenomenon is called *macroscale mixing*.

The fluctuating velocity gradients have an effect on smaller particles. In the turbulent mixing regime, these fluctuations are attributed to a finite number of impeller blades passing a finite number of tank baffles. For particle sizes typically less than 100 microns in size, turbulent properties of the fluid become an important consideration. Microscale mixing occurs in this regime.

As previously noted, all the power applied by an agitator to the fluid through the mixing impeller produces flow, velocity head, or shear. Through viscous shear, power is converted to heat at the rate of approximately 2,500 Btu/hour per Hp. Viscous shear, created only in the turbulent flow regime, is present at the microscale mixing level. Hence mixer horsepower per unit volume is the dominant component in microscale agitation. At very small particle sizes (less than, say, 1 micron), impeller geometry and type is of no consequence to viscous shear development and its effect on the particles—only the application of mixer power to generate shear is important. Experiments have shown that the power per unit volume in the impeller zone is about 100 times greater than in the rest of the tank.

Mixers are not specified for industrial applications to meet fluid mechanics parameters. Processes are so complex that it is impossible to isolate and define the effect of fluid mechanics on process results and mixer requirements. Pilot plant testing and experimentation affords a study of the sensitivity of a process to macroscale mixing variables (as a function of power, pumping capacity, impeller geometry, diameter, tip speed, and shear rate) as well as microscale mixing parameters (those related to power per unit volume, velocity fluctuations, etc.).

C. IMPELLER TYPES AND GEOMETRIES

Having discussed the basic concepts of fluid mechanics applicable to all impellers, we will present various practical impeller types used in industry today. The two basic types of impellers are radial and axial. Radial devices discharge fluid horizontally away from the impeller blades toward the tank wall. Axial flow impellers create flow vertically up or down away from the blades, parallel to the shaft. They produce more flow per unit power than do radial impellers and are more cost effective in flow controlled operations (i.e., solids suspension, blending, heat transfer, some mass transfer applications, etc).

Keeping in mind that a mixer is essentially a pump (albeit not a very efficient one), impeller power consumption creates flow and head. All the power that a mixer supplies to a fluid produces flow, head, or shear. At contant power, the relative amount of flow or shear applied to a fluid can be altered by changing the design of the impeller. Every impeller design creates some balance of flow and shear. There are no pure axial or radial flow impellers, although certain designs are predominantly axial or radial flow. A wide range of flow/shear ratios can be achieved by using different impellers. Fig. 1-3 shows the flow/head (shear) balance for common impeller types at constant power.

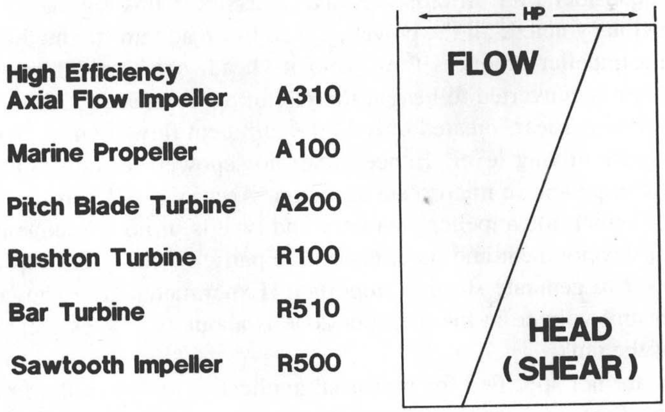

FIGURE 1-3. Impeller spectrum relating flow/head (shear) split at constant power for various types of impellers. (*Mixing Equipment, Inc.*)

Once the specific process requirements are known (i.e., whether the mixing application is flow or head (shear) controlling), the correct impeller type can be selected as the starting point in the design of the mixer.

At the top of the impeller spectrum are impellers with high flow and low shear rates. These are paddle types, large diameter gates, rakes, spirals, and anchors running close clearance to tank walls for high viscosity blending and non-Newtonian slurry suspension applications.

Next are axial flow impellers, including marine propellers, hydrofoils (variable pitch curved blade turbines), and fixed pitch flat blade axial flow turbines. These impellers are generally used for low to moderate viscosity blending, solid suspension, and heat transfer—processes requiring high pumping efficiencies.

For process results requiring progressively higher power per unit volume and/or more shear (head), the family of radial flow impellers becomes more practical. Flat bladed radial impellers, with blades at 90° to the impeller centerline, are often used for gas dispersion and mass transfer applications because of their well balanced flow/shear development.

Extremely high shear rates may be obtained (with relatively low flow production) by using narrow bladed bar turbines, sawtooth impellers, and homogenizers/colloid mills. These high shear impellers are used effectively for high shear dispersions of solids in liquids or liquids in liquids, as well as applications requiring solid size reduction in addition to dispersion (i.e., solids attritioning and dispersion).

Let us examine in closer detail the characteristics of this impeller spectrum. Fig. 1-4 shows the physical appearance and typical dimensions of those basic impellers.

The impeller in Fig. 1-4(a) has a disk and flat blades at 90° to the disk, and is known as the flat bladed radial flow or Rushton turbine. It is used for applications requiring balanced flow/head development with fairly high shear and turbulence formation. This turbine is particularly well suited for gas-liquid contacting because of its flat circular disk. When gas is introduced through a sparger below the impeller, the disk prevents the gas from bypassing the blades or flooding the turbine, instead forcing it on a path to the high shear zone along the lower blade edge.

Power response can be changed by varying the number of bolted blades on the predrilled disk. This measure provides flexibility in performance for any process changes.

The impeller shown in Fig. 1-4(b) is known as a bar turbine. Blades are normally welded in an alternating manner to the top and bottom of the disk as shown. Blade width and height are normally $1/20$ of impeller diameter. Of all the turbines shown in Fig. 1-4, this one produces the highest shear rate. It runs at relatively high speeds, requiring lower torque, and as such, a smaller speed reduction drive train is required than other radial flow turbines shown.

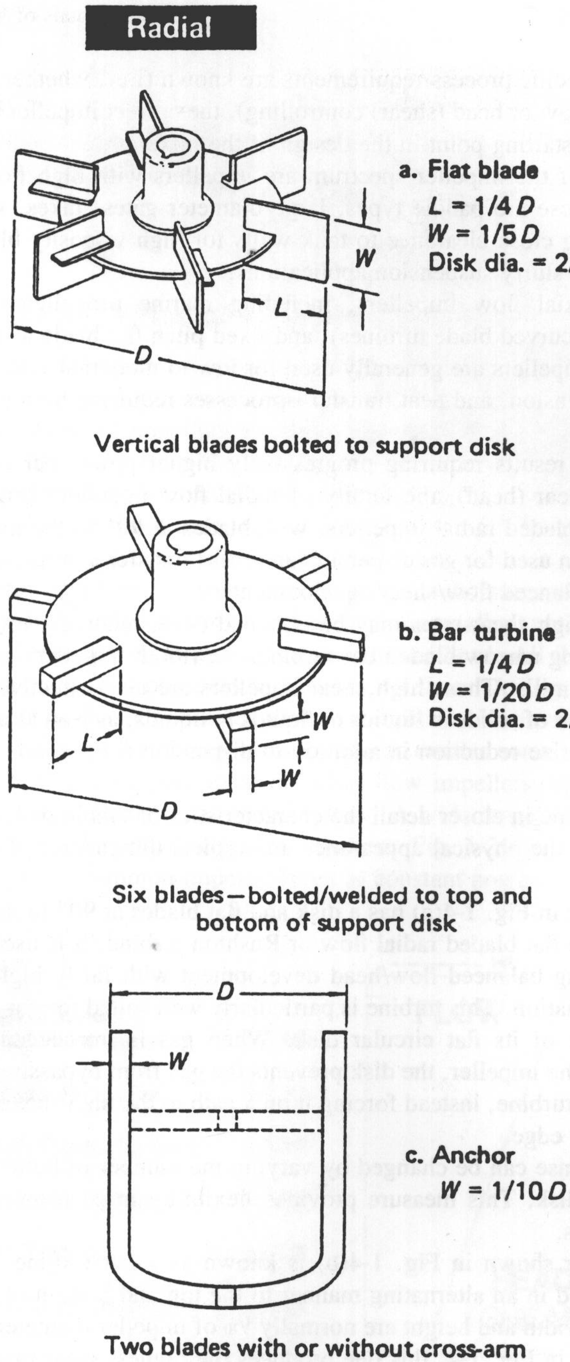

FIGURE 1-4(a–g). Impellers commonly found in process industries applications. (*Mixing Equipment, Inc.*)