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Fluid Mixing in 1989

Recent changes in mixing process technology have increased our understanding of process mechanics.

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What's new in fluid mixing? Let us list a few things, not necessarily in any order of importance because the order of importance depends upon the particular application of interest.

A new understanding of the fluid mechanics of impellers has resulted in the introduction of a variety of impellers to do specific things. Most of the new impellers are designed to give higher flow per horsepower. Unfortunately, the terms *high efficiency, high performance, super performance,* or *low energy* are often used for these impellers. Unless carefully defined, this ignores the fact that different processes have different requirements for flow, fluid shear, and other fluid mechanic properties. In my opinion, it is better to describe what is meant by the characteristics of the impeller performance rather than to use vague terms.

Scale up is often the major concern of chemical engineers when it comes to fluid mixing processes. A new understanding of the role of micro- and macroscale mixing has continued to evolve. There is a better understanding of the role that geometry and, perhaps (or perhaps not), geometric similarity play in selecting pilot- and full-scale equipment with comparable fluid mixing process characteristics. This has been coupled with work on numerical fluid mechanics and an understanding of the potential role of the k-ϵ spectrum for modeling chemical reactors.

The role of viscosity in the performance of impellers, both in terms of fundamental fluid mechanics and in some of the basic components that are of concern with any mixing process (such as blend time, flow pattern, and heat transfer), is being discovered by better and more extensive experiments.

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The fact that impellers with a traditional axial flow shape tend to change their discharge flow pattern from axial flow at high Reynolds numbers to radial flow at low Reynolds numbers gives a better appreciation of the role that viscosity can play in process performance.

Biotechnology is on everyone's agenda these days. The cultivation of animal cells that must be attached to a surface has brought up an intriguing set of problems. In addition, there are very sensitive cells made by genetic engineering techniques that have more diverse requirements for cultivation. This has led to the proliferation of many mixing devices other than impeller mixers, in part because many animal cell cultures require 7–20 weeks for processing rather than the 5–7 days common in antibiotic fermentation processing. This requires that attention be given to developing equipment that can be maintained aseptic for long periods of time.

There are more and more "unusual" fluid and slurry systems being processed. In the pulp and paper industry, there are many advantages to carrying out chemical processes at high pulp consistency (concentrations). Traditionally, pulp concentrations around 6 or 7% (by weight) have been the maximum that flow with definable fluid properties. Attention has now turned to pulps of 6 to 12% (by weight) in which fluid motion in the traditional sense does not occur. Various fluidizing techniques can, however, be used for mixing. The desire to process high-consistency pulps (12–25% by weight) puts us into a new arena where macro- and microscale mixing are important for both process experimentation and design.

The limitations of forming impellers from a piece of flat stock has limited the application of fluid mechanics to some degree. Composite shafts and impellers, which were developed mainly for corrosion resistance and to be competitive and economical with stainless steel and other higher alloys,

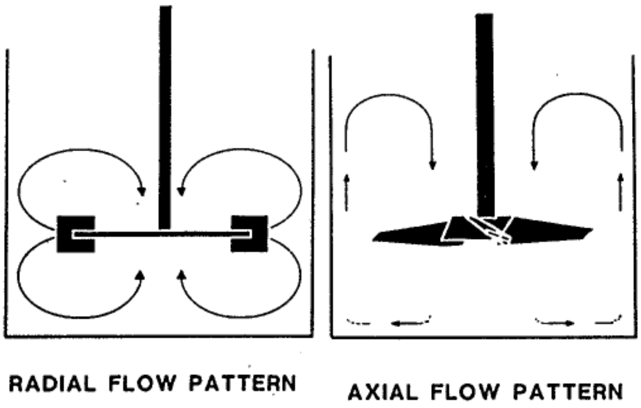

Figure 1. Typical true axial and radial flow patterns.

are now available. Composite materials, however, also allow us to use very efficient fluidfoil shapes that permit increased flow and reduced shear rates.

Gas–liquid mass transfer is affected greatly by fluid mixing variables. New axial flow impellers with high-solidity ratio have given much different performance than the commonly used radial flow turbines.

These are but a sampling of what is going on today in fluid mixing, and we will again discuss them as we go through this review.

Basic flow patterns

First, let us define three basic flow patterns. True axial flow patterns, shown in Figure 1, usually exist only when a fluidfoil approach has been used in designing the impeller blades. Properly done, a very uniform axial flow pattern leaves the impeller zone; it appears almost as if a solid draft tube confines the flow. This flow pattern can persist for two to five impeller diameters from the impeller before it starts to expand. At the other extreme is radial flow, which exists mainly when a disk-type impeller is used. The uniform pressure drop across a disk impeller allows the radial flow pattern to develop.

A radial flow impeller without a disk tends to have either an upward or a downward axial component of flow. The pressure drop across the impeller is never uniform in the vertical direction, and it depends upon the location of the impeller relative to the tank bottom and its proximity to other impellers.

The traditional axial flow turbine shown in Figure 2 often has a blade that is 45° from the horizontal and a blade-width-to-impeller diameter of approximately one-fifth. This impeller tends to produce a flow that has a discharge angle about 45 to 60° from the horizontal. Axial flow turbines typically have a wide velocity difference across the impeller discharge zone. Upflow may occur in the hub area of the impeller. The axial flow fluidfoil impeller shown in Figure 3 tends to give a different velocity pattern as shown in Figure 4.

A parameter of interest with fluidfoil impellers is the solidity ratio of the blades. This is illustrated in Figure 5, which shows the solidity ratio of an A310 impeller by comparing the projected blade area to a disk of diameter equal to the swept-out diameter of impeller. There is always a possibility of some confusion with respect to the actual swept-out diameter of an impeller unless the effect of material thickness and other parameters on the impeller diameter are considered. As a reminder and a caution, when calculating whether or not an impeller will go through a manhole, the maximum swept-out diameter for the particular materials and thickness of construction used in the impeller must be known.

Fluidfoil impellers produce a pressure field around the impeller, and the lift and drag coefficients that make up this pressure field determine the pumping capacity. The drag coefficient depends upon the shape and solidity ratio of the blades. For low-viscosity fluids where the Reynolds number of the impeller is around 1,000 or higher, the optimum solidity ratio is about 15 to 30%.

For any given impeller type, there must be sufficient strength at the blade and hub area to take care of the fluid or mechanical forces on the impeller. This requires a minimum blade area for a given pressure loading across the blade. Much thought, experimentation, and calculation must go into deciding the minimum blade area. In general, a three-bladed axial flow impeller can be made to have a better pumping performance than a blade impeller with four or more blades while having sufficient mechanical strength.

The number of impeller blades can range anywhere from 2 to 12 or more. Two blades are normally not sufficiently hydraulically and mechanically stable to allow their use on large mixers at high power levels. On the other hand, there is usually not much advantage to a fluidfoil impeller with 4 or more blades, unless there is a need to operate at a low Reynolds number or some other specific process requirement.

Another important parameter is the size of the hub area. For operation in an open tank, the traditional hub diameter of approximately 10–15% of the impeller diameter is ade-

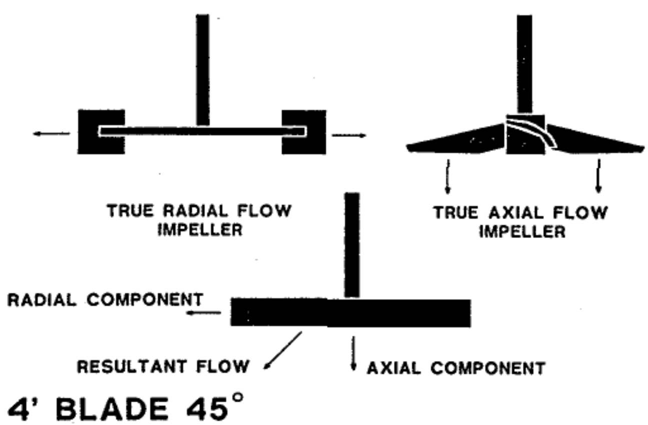

Figure 2. Axial flow pattern with radial component from axial flow turbine impellers.

Impeller identification

All of the impellers referred to in this paper are produced by the Mixing Equipment Co. and identified by a proprietary number. Unfortunately, there is no universal nomenclature available to completely describe the impellers.

> More and more 'unusual' fluid and slurry systems are being processed.

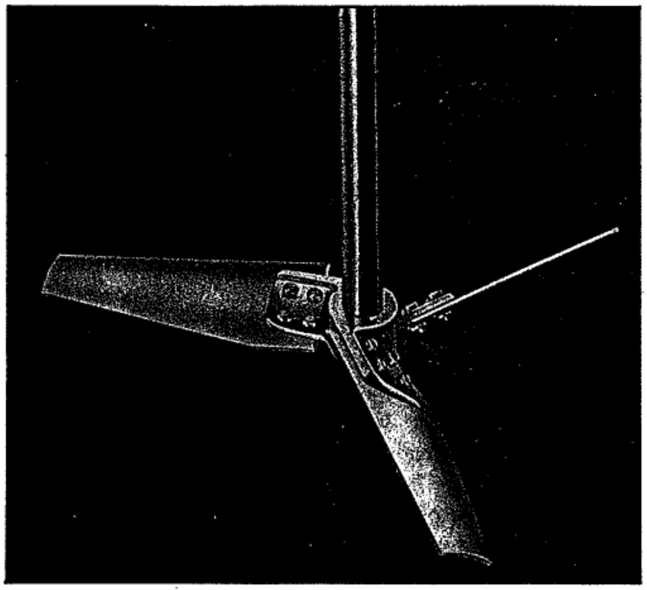

Figure 3. A310 fluidfoil impeller.

quate because there is insufficient resistance to make upflow (or backflow) in the hub area possibile. On the other hand, impellers that are to be used in draft tubes should have a relatively large hub area to physically prevent backflow into the hub area of the impeller. Backflow is a result of the higher system heads inherent in a draft tube system.

Impeller types

Impellers made of composite materials. When impellers are made out of composite materials, an almost infinite selection of shapes is possible. The impeller shown in Figure 6 is probably the one providing the highest flow and lowest shear rate for a given power level of any available

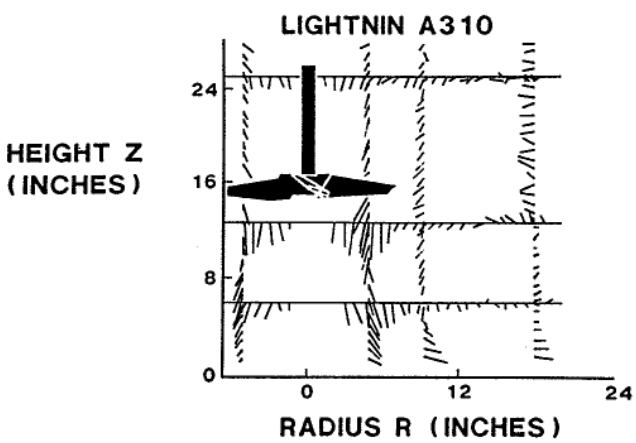

Figure 4. Typical average velocity profile measured by a laser-droppler velocity meter for the A310 impeller in Figure 3.

commercial impeller. The blade profiles are patterned after the ideal fluidfoil section. Blade tips (commonly called proplets), which effectively eliminate any tendency for the flow to recirculate (often called vortex shedding) around the blade tips, have also been incorporated. Proplets can add about 10% to the flow, but the velocity head component is reduced by 10%.

Impellers with high-solidity ratios. At a Reynolds number of approximately 200, the discharge flow pattern of an A310 impeller becomes more radial. If we continue on to lower Reynolds numbers, the low-solidity ratio of the A310

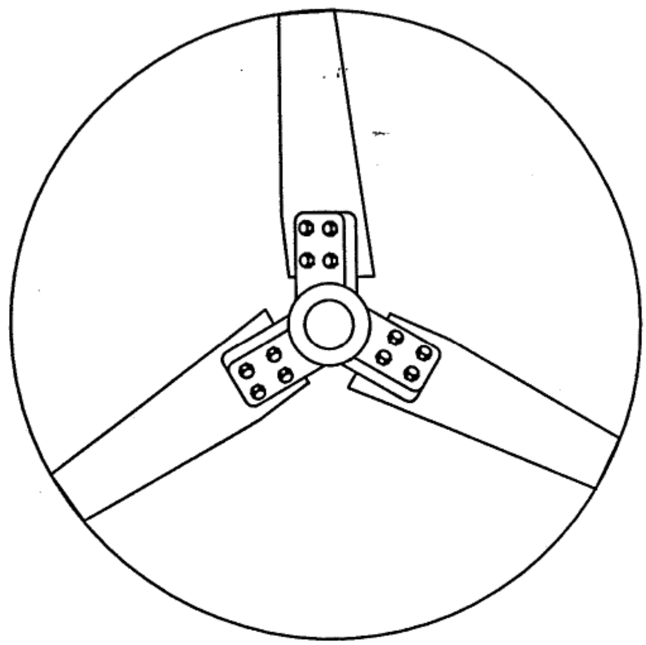

Figure 5. Illustration of the solidity ratio for axial flow impellers.

reduces its effectiveness markedly. A traditional A200 impeller is more effective at a low Reynolds number for overall circulation and for use in blending processes.

At Reynolds numbers in the vicinity of 1,000 to 10,000, pseudoplastic, Bingham plastic, or viscoelastic materials require a higher solidity ratio for more effective results. This led to the development of the A312 impeller, which is used with paper-pulp suspensions and in applications where materials with significant pseudoplastic properties are present.

With gas dispersions, low-solidity axial flow impellers like the A310 or the A200 tend to flood at relatively low gas velocities compared to the more traditional radial flow impellers equipped with a disk. This has led to the development of the A315 impeller, Figure 7, which has a solidity ratio of approximately 90%. In fact, in the area around the hub there is some overlap between the four blades of an A315.

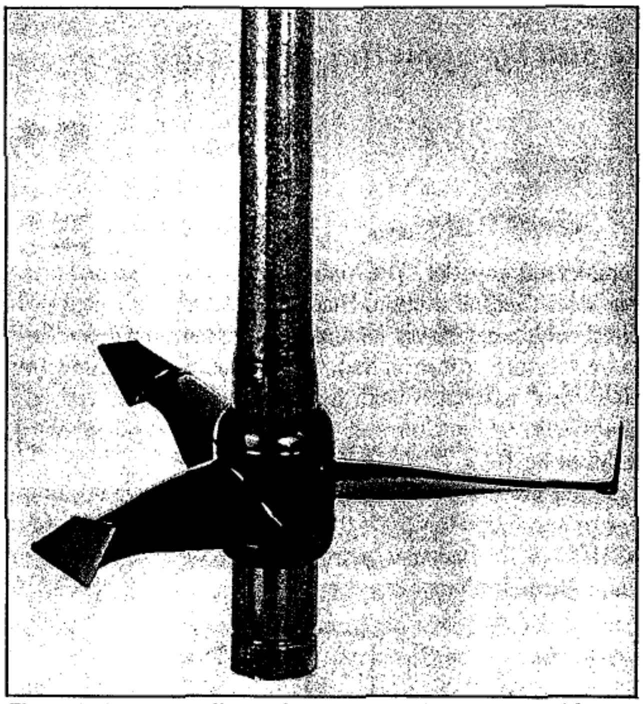

Figure 6. A6000 impeller made from composite materials with carefully shaped airfoil design.

This impeller has other unique characteristics that will be discussed.

Multiple impellers. Many engineers use multiple impellers when the liquid-depth-to-tank-diameter (Z/T) ratio gets above 1.0. In the case where the Z/T ratio is 1.2, using two radial flow turbines equipped with a disk establishes four flow pattern zones in the tank, two for each impeller. As shown in Figure 8, using two A200 axial flow turbines tends to give two zones of action because the discharge pattern from each impeller is approximately at 45° from the horizontal.

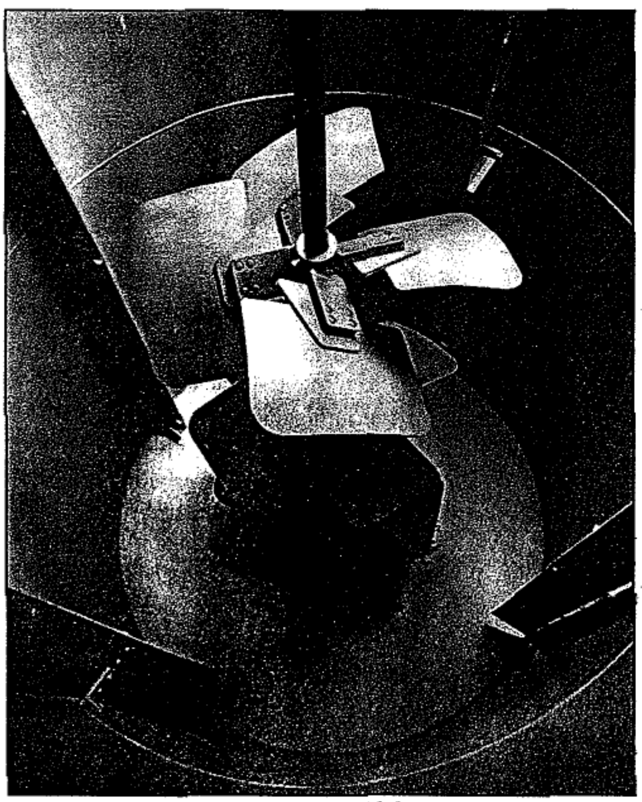

Figure 7. Typical impeller for gas–liquid dispersion, solidity ratio of 0.85.

In both of the above cases, at a given speed there is approximately twice the flow with two impellers as with one. The zones are readily observed by putting color indicators in the tank and observing how long it takes to blend within a zone between the zones. As a general guide, the blend time between two zones is about 10 times longer than the blend time within a zone.

I have actually observed cases where there can be a measurable temperature difference between these zones in a mixing vessel when highly exothermic reactions are involved. As much as a 10°F (4.7°C) temperature difference can be observed; this, however, is extreme. If the blend time between the zones is short relative to the batch time or continuous residence time, the presence of these zones in a tank is not likely to affect the process.

With two fluidfoil impellers, one impeller feeds the other with approximately the same flow as it would develop on its own. (The system operates like a two-stage pump, in which one gets twice the head at the same flow with two pumps as compared to one.) This insures that the flow will circulate at a uniform flow pattern from top to bottom, effectively eliminating the zoning tendency. The loop-type flow pattern that is set up, however, does not have the random particle interchange typical of axial flow turbine impellers. The mixing that results is similar to that obtained with an axial flow impeller in a draft tube.

Total pumping throughout the vessel can be achieved with dual A310 impellers. One characteristic of fluidfoil impellers is that they tend to recirculate returning flow very quickly into the suction plane of the impeller. The preferred coverage is also relatively low compared to the axial flow turbines. Fluidfoil impellers also do not form a marked vortex, and they do not have the ability to suck down dry solids on the fluid surface.

Recent fluid mechanics studies

If the fluid discharge from an impeller is measured with a device that has a high-frequency response, one can track the velocity of the fluid as a function of time. The velocity at a given point in time can then be expressed as an average velocity (v) plus fluctuating component (v'). Average velocities can be integrated across the discharge of the impeller and the pumping capacity normal to an arbitrary discharge plane can be calculated. This arbitrary discharge plane is often defined as the plane bounded by the boundaries of the impeller blade diameter and height. Because there is no casing, however, an additional 10–20% of flow typically can be considered as the primary flow of an impeller.

The velocity gradients between the average velocities operate only on larger particles. I typically think of this larger size as greater than 1,000 μm. This is not a proven definition, but it does give a feel for the magnitudes involved. What we have defined is macroscale mixing.

Smaller particles primarily see the fluctuating velocity component. In the turbulent region, these fluctuations arise

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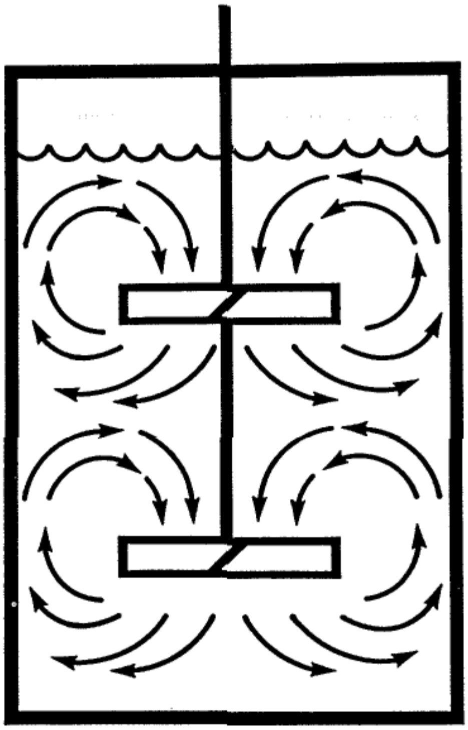

Figure 8. A200 flow pattern with dual axial flow turbines.

from the finite number of impeller blades passing a finite number of baffles. These set up velocity fluctuations that can also operate on the macroscale. When the particle size is much less than 100 μm, however, the turbulent properties of the fluid become important. This is my definition of the boundary size for microscale mixing.

All of the power applied by a mixer to a fluid through the impeller appears as heat. The conversion of power to heat is through viscous shear and is approximately 2,500 Btu/h/hp (750 w/h/hp). Viscous shear, present only in turbulent flow, is at the microscale level; as a result, the power per unit volume is a major component of the phenomena of microscale mixing. At a 1-μm level, in fact, it doesn't matter what specific impeller design is used to apply the power.

Numerous experiments show that the power per unit volume in the zone of the impeller (which could be about 5% of the total tank volume) is about 100 times higher than the power per unit volume in the rest of the vessel. Making some reasonable assumptions about the fluid mechanics parameters, the root-mean-square (rms) velocity fluctuation in the zone of the impeller appears to be approximately 5–10 times higher than in the rest of the vessel. This conclusion has been verified by experimental measurements.

The ratio of the rms velocity fluctuation to the average velocity in an impeller zone is about 50% with many open impellers. If the rms velocity fluctuation is divided by the average velocity in the rest of the vessel, however, the ratio is on the order of 5 to 10%. This is also the level of rms velocity fluctuation to the mean velocity in pipeline flow. There are phenomena in microscale mixing that can occur in mixing tanks that do not occur in pipeline reactors. Whether this is good or bad depends upon the process requirements.

Figure 9 shows velocity vs. time for three different impellers. The differences between the impellers are quite significant and can be important for chemical reactors.

The velocity spectra in the axial direction for an axial flow impeller A200 is shown in Figure 10. A decibel correlation has been used in Figure 10 because of its well-known applicability in mathematical modeling as well as the practicality of putting many orders of magnitude of data on a reasonably sized chart. Other spectra of importance are the power spectra (the square of the velocity) and the Reynolds stress, (the product of the R and Z velocity components) and a measure of the momentum at a point.

The ultimate question is this: How do all of these spectra

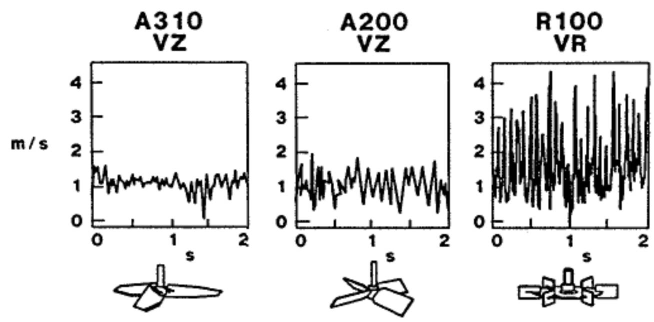

Figure 9. Comparison of velocity vs. time measurements from three different impeller types, all with the same total impeller pumping capacity.

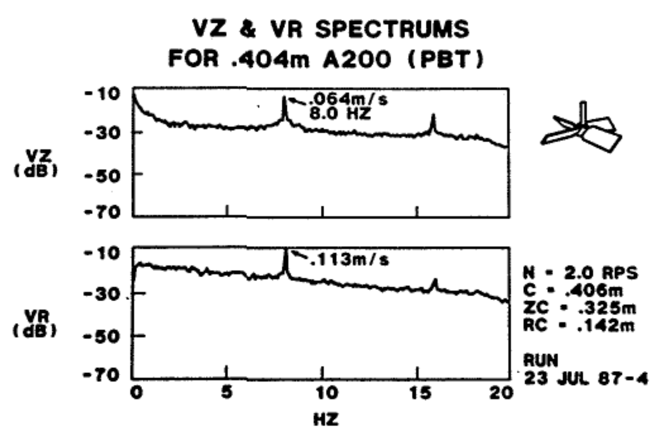

Figure 10. Spectrum analysis of velocities at a point.

apply to process design and mixing vessels? No one today is specifying mixers for industrial processes based on meeting criteria of this type. This is largely because processes are so complex that it is not possible to define the process requirements in terms of these fluid mechanics parameters. If the process results could be defined in terms of these parameters, sufficient information probably exists to permit the calculation of an approximate mixer design. In my opinion, it is important to continue studying fluid mechanics parameters in both mixing and pipeline reactors to establish what is required by different processes in fundamental terms.

Recently, the most practical result of these studies has been the ability to design pilot plant experiments (and, in some cases, plant-scale experiments) that can establish the sensitivity of a process to macroscale mixing variables (as a function of power, pumping capacity, impeller diameter, impeller tip speed, and macroscale shear rates) in contrast to microscale mixing variables (which are related to power per unit volume, rms velocity fluctuations, and some estimation of the size of the microscale eddies).

Another useful and interesting concept is the size of the eddies at which the power of an impeller is dissipated. This development utilizes the principles of isotropic turbulence developed by Komolgoroff. The calculations assume some reasonable approach to the degree of isotropic turbulence, and the estimates do give some idea as to how far down in the microscale size the power per unit volume can effectively reach.

$$L \approx (\nu^3/\epsilon)^{1/4}$$

Scaleup/scale down

Two aspects of scaleup frequently arise. One is building a model based on pilot plant studies that develop an understanding of the process variables for an existing full-scale mixing installation. The other is taking a new process and studying it in the pilot plant in such a way that pertinent scaleup variables are worked out for a new mixing installation.

There are few principles of scaleup that can tell us what approach to take in either case. Using geometric similarity, the macroscale variables can be summarized as follows:

- Blend and circulation times in the large tank will be much longer than in the small tank.
- Maximum impeller zone shear rate will be higher in the larger tank, but the average impeller zone shear rate will be lower; therefore, there will be a much greater variation in shear rates in a full-scale tank than in a pilot unit.
- Reynolds numbers in the large tank will be higher, typically on the order of 5 to 25 times higher than those in a small tank.
- Large tanks tend to develop a recirculation pattern from the impeller through the tank back to the impeller. This results in a behavior similar to that for a number of tanks in a series. The net result is that the mean circulation time is increased over what would be predicted from the impeller pumping capacity. This also increases the standard deviation of the circulation times around the mean.
- Heat transfer is normally much more demanding on a large scale. The introduction of helical coils, vertical tubes, or other heat transfer devices causes an increased tendency for areas of low recirculation to exist.
- In gas–liquid systems, the tendency for an increase in the gas superficial velocity upon scaleup can further increase the overall circulation time.

What about the microscale phenomena? These depend primarily on the energy dissipation per unit volume, although we also must be concerned about the energy spectra. In general, the energy dissipation per unit volume around the impeller is approximately 100 times higher than in the rest of the tank. This results in an rms velocity fluctuation (ratioed to the average velocity) on the order of 10:1 between the impeller zone and the rest of the tank.

Because there are thousands of specific processes each year that involve mixing, there will be at least hundreds of different situations requiring a somewhat different pilot plant approach. Unfortunately, no set of rules states how to carry out studies for any specific program, but here are a few guidelines that can help one carry out a pilot plant program:

- For any given process, take a qualitative look at the possible role of fluid shear stresses. Try to consider pathways related to fluid shear stress that may affect the process. If there are none, then this extremely complex phenomena can be dismissed and the process design can be based on such things as uniformity, circulation time, blend time, or velocity specifications. This is often the case in the blending of miscible fluids and the suspension of solids.
- If fluid shear stresses are likely to be involved in obtaining a process result, then one must qualitatively look at the scale at which the shear stresses influence the result. If the particles, bubbles, droplets, or fluid clumps are on the order of 1,000 μm or larger, the variables are macroscale and average velocities at a point are the predominant variable.

Velocity Data

The average velocity at a point can be used to calculate the pumping capacity of the impeller. By measuring these velocity vectors throughout the entire vessel, it is possible to calculate the total flow throughout the entire mixing vessel. Defining the discharge area of the impeller, however, is somewhat arbitrary because there is no casing around it as there is in a pump. This means that the definition of the pumping capacity of any impeller is also somewhat arbitrary. In addition to measuring the total flow in a tank, one must understand the mode in which the flow in the tank tends to rotate. There is a conversion of the higher velocity from the impeller to a lower average velocity and bulk flow throughout the tank. Because this is carried on throughout the tank, the total circulation flow in a tank can be anywhere from 10 to 1,000% higher than the primary flow from the impeller through the impeller discharge area.

Impeller fluid mechanics studies between 1982 and 1984 dealt primarily with the average velocity at a point. Ways of maximizing the pumping capacity of the impeller at the expense of fluid shear rates and microscale mixing were developed. There are more processes that require high flow with an almost negligible requirement for fluid shear and microscale mixing. Unfortunately, for a given power level, increasing the total flow comes at the expense of macro- and microscale shear rates.

Processes are so complex that it is not possible to define process requirements using parameters that involve fluid mechanics.

When macroscale variables are involved, every geometric design variable can affect the role of shear stresses. They can include such items as power, impeller speed, impeller diameter, impeller blade shape, impeller blade width or height, thickness of the material used to make the impeller, number of blades, impeller location, baffle location, and number of impellers.

Microscale variables are involved when the particles, droplets, bubbles, or fluid clumps are on the order of 100 μm or less. In this case, the critical parameters usually are power per unit volume, distribution of power per unit volume between the impeller and the rest of the tank, rms velocity fluctuation, energy spectra, dissipation length, the smallest microscale eddy size for the particular power level, and viscosity of the fluid.

• The overall circulating pattern, including the circulation time and the deviation of the circulation times, can never be neglected. No matter what else a mixer does, it must be able to circulate fluid throughout an entire vessel appropriately. If it cannot, then that mixer is not suited for the tank being considered.

Qualitative and, hopefully, quantitative estimates of how the process result will be measured must be made in advance. The evaluations must allow one to establish the importance of the different steps in a process, such as gas–liquid mass transfer, chemical reaction rate, or heat transfer.

• It is seldom possible, either economically or timewise, to study every potential mixing variable or to compare the performance of many impeller types. In many cases, a process needs a specific fluid regime that is relatively independent of the impeller type used to generate it. Because different impellers may require widely different geometries to achieve an optimum process combination, a random choice of only one diameter of each of two or more impellers may not tell what is appropriate for the fluid regime ultimately required.

• Often, a pilot plant will operate in the viscous region while the commercial unit will operate in the transition region, or alternatively, the pilot plant may be in the transition region and the commercial unit in the turbulent region. Some experience is required to estimate the difference in performance to be expected upon scale up.

• In general, it is not necessary to model *Z/T* ratios between pilot and commercial units.

• In order to make the pilot unit more like a commercial unit in macroscale characteristics, the pilot unit impeller must be designed to lengthen the blend time and to increase the low maximum impeller zone shear rate. This will result in a greater range of shear rates than is normally found in a pilot unit.

All of these conditions can be met using smaller *D/T* ratios and narrower blade heights than are used normally in a pilot unit. If one uses the same impeller type in both the pilot and commercial units, however, it may not be possible to come close to the long blend time that will be obtained in the commercial unit. I believe that radial flow impellers can be excellent models in a pilot plant unit for axial flow impellers in a commercial unit.

• The performance of the new fluidfoil impellers that develop a much higher flow pattern and, therefore, a shorter blend time may not seem outstanding in pilot unit studies. Unfortunately, a pilot unit usually is already too good a blending device compared to what happens in a commercial unit.

• If the overall process result is primarily a function of the total integrated mass transfer rate per unit volume, then there is usually very little difficulty in obtaining this process result in a commercial unit that is based on studies done at a pilot scale. There is no great problem today in measuring and correlating K_s, K_{ga}, or K_{lg} values in liquid–solid, liquid–gas, and liquid–liquid mass transfer processes.

• There is always a minimum-size pilot plant. Let us say that the blade height is one centimeter. If the maximum impeller zone shear rate at the boundary of the discharge stream has a value of 10 reciprocal seconds, then the shear rate across ⅛ cm would be 9.5, across ¼ cm it is 7.0, and across ⅝ cm it is 5.0. A shear rate of 5 is also approximately the average impeller zone shear rate.

The shear rate across a 1-cm particle is zero because we have the same velocity on both sides of the impeller blade. This means that a small particle would see a shear rate of 10 while a 1-cm particle would see a shear rate of zero. This leads to the general and very practical rule that the height of the impeller blade or the width of the impeller discharge stream must be at least four times larger in dimension than the biggest particle that we want to affect in a process.

High viscosity, biotechnology, and paper pulp

High viscosity. A Reynolds number less than 10 characterizes high viscosity. In a pilot unit, this occurs at a viscosity of approximately 5,000 cps; in a commercial unit, the viscosity is on the order of 50,000 cps.

As the viscosity and the pseudoplastic characteristics of the impeller become higher, the flow pattern from a typical axial flow turbine impeller begins to become radial in nature. At some point it may not be able to have an overall process circulation. When this happens, one can resort to helical or anchor impellers with a close clearance to the tank wall. There is a significant difference in the characteristics of these impellers and turbine impellers. They nor-

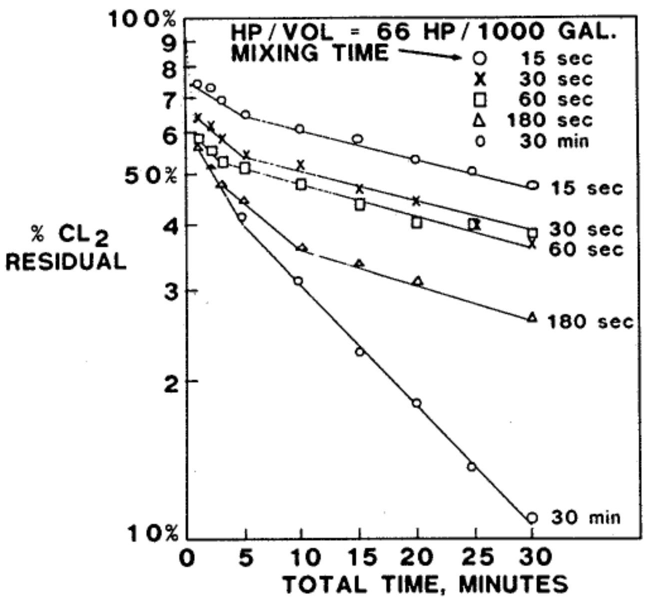

Figure 11. The effect of mixer power and residence time on the chlorination of paperstock.

mally require about 1/5 to 1/10 of the horsepower of a turbine impeller for the same overall circulation pattern. While visually they appear efficient, the microscale energy dissipation rate is much larger for turbine impellers.

Classical fluid mechanics analysis is particularly appropriate where high viscosity is present. The fluidflow patterns are around various shapes and objects, and the general nature of the boundary layer is somewhat more predictable than when turbulent flow is developed.

The A310 impeller will have few advantages below a Reynolds number of 200. Here an axial flow turbine is generally preferable, and there is considerable room for impellers with very wide blade areas; impellers with a blade height equal to the impeller diameter may offer advantages. Special versions of the A315 impeller shown in Figure 7 have proved to be particularly effective for certain high-viscosity operations.

Biotechnology. Mixers have been used in fermentation processes for many years. The biological materials used in fermentation are free swimming with a cell wall that has a certain resistance to fluid shear stress damage. The sensitivity of various microbial cells to shear rates, however, varies over a wide spectrum. Concern has constantly been expressed over the role that fluid shear may play in the productivity of the various processes.

The newest biotechnological area involves the use of animal cells. These cells do not have a cell wall and are just like a "bag" of fluid suspended in the medium; they often must attach themselves to a surface in order to grow and reproduce. A very promising technique for increasing the surface area of the biological reactor needed for the attachment of these cells is the use of inert solids on which the cells can grow. Depending upon the size of the cell and the size of the surface irregularities in the microcarrier, the cells may grow either inside the microcarrier (in what are essentially caves) or on the surface.

Excessive impeller shear rate can have two different effects. The bond between the mammalian cells and the microcarrier can be broken, exposing the cell to shear stress damage in the free liquid medium. In addition, the metabolism of cells may be inhibited, which reduces their ability to produce new cells. Studies to date have shown that the cell metabolism is not easily harmed by increasing the power level of a mixer. At some point, however, the cells will break away from their attachment to the surface; however, the amount removed can be measured easily.

Depending upon the scale being practiced, mixing systems (devices) other than impeller mixers may be practical. This includes placing the microcarriers in essentially two-phase reactors through which nutrient streams pass or, perhaps, diffuse through the equipment boundaries. Other techniques use airlift-type motion or fluid jets.

Fluidfoil impellers have been successfully applied in many of these newer mammalian cell reactors. If these impellers are used on a small scale, however, it will be very difficult later to obtain the required blend time and the appropriate shear rate on a commercial scale.

Active work continues on a variety of options in these processes, and the final, practical result will probably be somewhat different depending upon the process involved.

Paper pulp suspensions. An A310 impeller does not have sufficient solidity to be effective in the suspension and blending of paper pulp. It has been found that an impeller with a solidity ratio approximately twice that of the A310 provides a very effective flow pattern throughout a vessel.

An area being intensively studied and discussed is that dealing with the mixing of high-consistency stock. Figure 11 shows some measurements on the effect of mixer power on the chlorination of low-consistency pulp (approximately 4% pulp by weight). Looking at medium-consistency pulps of 6 to 12% pulp by weight, the stock can no longer be moved even at power levels considerably higher than those used with the low-consistency pulp. There appears to be a certain threshold of power needed to "fluidize" the pulp so that chemical diffusion and reaction can occur effectively and uniformly.

With high-consistency pulp, 12–25% pulp by weight, there really is no analogy to fluid mixing or even viscosity that one can utilize to guide the studies. The economics of being able to process high-consistency pulp are so important that studies are underway to determine what role fluid mixing principles can indeed play in this arena.

Other factors

Heat transfer. The axial discharge of the fluidfoil impellers (and the consequent axial upflow) is not particularly effective for helical coil heat transfer. Even though the total

> *Microscale phenomena depend primarily on the energy dissipation per unit volume.*

flow for a given power level is higher than with other axial or radial flow impellers, the heat transfer performance does not increase and may actually decrease. If an A310 type of impeller is required for a process, it is normally necessary to accept the heat transfer consequences. One can try to modify the coil design or its placement to more effectively use the very axial flow pattern of the fluidfoil impellers.

A general principle to remember with mixers for heat transfer is that the increase in the heat transfer coefficient with power has a very low exponent, on the order of 0.2. This means that to increase the heat transfer coefficient by 15%, the power must almost double. One must first estimate the coefficient that will be obtained at the forced convection point and then calculate the required coil area. One should take advantage of any power designed into the mixer for other process requirements that exceed the requirement for forced convection for the heat transfer services and again calculate the surface area. It is not normally practical to attempt to improve heat transfer coefficients by increasing mixer power levels.

Gas–liquid mass transfer. Much of the interest in fluidfoil impellers for gas–liquid processes came from studies directed at retrofitting existing fermentation tanks. These tanks typically had power levels from 5 to 25 hp (1 to 5 kW/m^3) per 1,000 gal (3.785 m^3). Most often, multiple radial flow R100 impellers on a mixer were used. Superficial gas velocities were on the order of 0.1–0.5 ft/s (0.03–0.15 m/s).

A more efficient blending impeller gives better results when a sufficient or excess gas–liquid mass transfer ability is provided by the existing mixer and air rate. A nonuniform oxygen concentration through the tank can exist because of poor blending. However, some damage may occur

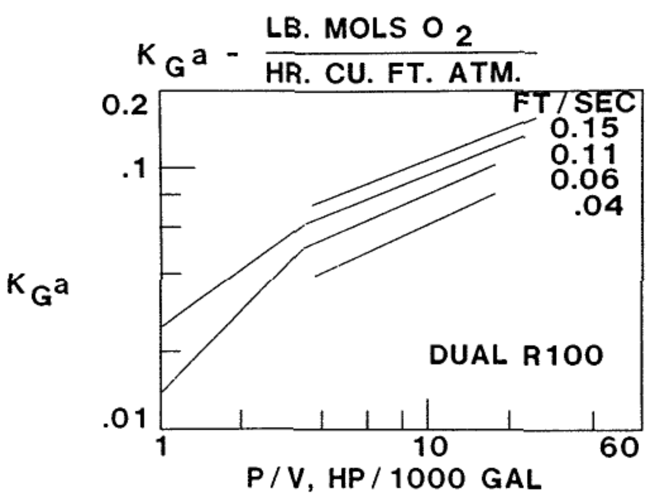

Figure 12. Typical plot of K_{ga} for the R100 radial flow turbine as a function of the power and gas rate using an oxygen–sodium sulfite system.

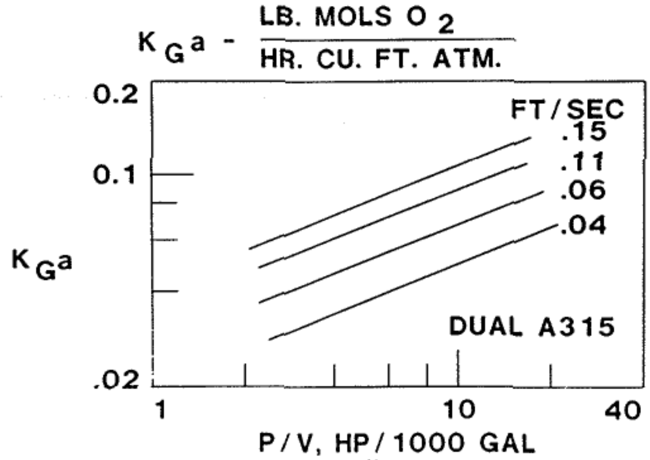

Figure 13. Typical curve of K_{ga} vs. power and gas rate for the A315 impeller using an oxygen–sodium sulfite system.

to the organism from the high energy level going into macro- and microscale shear rates from the radial flow impellers. Replacing one or two of the radial flow R100 impellers with A310 impellers, normally at the top of a vessel, was only partially successful—the success-to-failure ratio was approximately 2:1. After examining the parameters of the processes that did not improve, it was determined that the visual flooding of the gas through A310 impeller types was very high.

After considerable study, the A315 impeller, which has a solidity ratio of about 85% and is shown in Figure 7, was developed. This impeller dramatically improved the physical dispersion of gas going through the unit; the mass transfer coefficient vs. mixer power level at various gas rates differed significantly from that of the R100 impeller. Experimental data on the basic mass transfer characteristics of the A315 impeller are still being collected, but three things are clear.

- Figure 12 shows that the slope of K_{ga} as a function of the power and gas rate has a marked break point for a radial flow turbine. As shown in Figure 13, this characteristic is not exhibited by an A315 impeller. Obviously, with two different curves like this there can be some areas where one of the impellers is more effective in terms of gas–liquid mass transfer.

Those who model chemical reactors must have some idea of the fluid mechanics throughout a vessel. In particular, they need some estimate of the energy spectrum, expressed as the (k-ε) spectra. The (k-ε) spectra can be estimated from suitable measurements of the energy spectrum by hot wire, hot film, or laser-doppler velocity measurements.

(For additional information about velocity data, see the article on "Flow in the Impeller Region of a Stirred Tank" by Richard Calabrese and Carl Stoots in this issue.)

• Retrofitting existing mixers is common. Typically, this involves keeping the mixer power and mixer speed the same while changing the impellers. As a result, one is maintaining essentially constant torque on the equipment. In order to do this, the A315 impeller must be somewhat larger because its power number is lower than the R100.

When the ratio of *D/T* for a radial flow impeller is on the order of 0.35 to 0.4, the gas–liquid mass transfer characteristics of the A315 impeller will be better than those of the R100 impeller. Mass transfer and, in general, the overall blending flow pattern will be improved. There are, however, situations where this combination does not improve the process. In 5–20% of our trials, we found no improvement or even a decrease in performance when replacing R100s with A315s.

• Some ask, "In going to the A315 impeller, is it better to replace only the upper one or two impellers, maintaining the lower one or two impellers of the R100 type, or should the entire assembly be A315 impellers?" We don't know. Quantitative data gathering is still going on, and the question is an open one.

Composite impellers and numerical fluid mechanics

Impellers made of composite materials. Composite impellers have the flexibility of allowing almost any blade shape that can improve the fluidfoil characteristics; this advantage is used in the A6000 shape, which has a significant improvement in pumping capacity.

The basic shapes of composite impellers have been established and most of the current activity is directed at the mechanics of fabricating impellers, fabricating shafts, and working out methods of attaching the composite impeller to the composite shaft and attaching the composite shaft to the steel shaft from the speed reducer. There are questions regarding the proper composition of the surface layer of the composite material needed to resist corrosion, temperature, and abrasion. At some point in time, the basic cost of composite materials may be less than for an equivalent mixer in metal. Composite impellers and shafts may well be used in a majority of applications in the near future.

Numerical fluid mechanics. Numerical fluid mechanics can, potentially, carefully define many of the fluid mechanics parameters for an overall reactor system. Many of the models break the mixing tank up into many small microcells. Suitable material and mass transfer balances between these cells throughout the reactor are then made. This can involve very long, very massive computational requirements. Programs are available that can give reasonably acceptable models of experimental data taken in mixing vessels. Modeling the three-dimensional aspect of a flow pattern in a mixing tank, however, is a very formidable task.

For pipe flow and impeller blade shapes in pumps, some very specific fluid mechanic problems are now understood, and some explicit solutions are now available.

One thing that has hindered the widespread use of numerical fluid mechanics in mixing processes is the very illusive nature of the complex phenomena involved in any practical process. One usually does not know the fluid mechanics necessary to achieve a particular process result, and the process result itself is often very difficult to describe outside of an overall product evaluation or process yield. Exploring these mathematical techniques will certainly be valuable in the long run, but it is presently very difficult to suggest a particular economic advantage that will result from any given numerical fluid mechanics study. ■

Suggested reading

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Nomenclature

N, impeller speed;
D, impeller diameter;
T, tank diameter;
Z, liquid level;
N_p, power number;
N_q, flow number;
H, velocity head, $v^2/2g$;
P, power;
K_{ga}, mass transfer coefficient, gram-moles/second/cubic meter/bar;
L, length scale;
ν, fluid velocity;
v' fluid velocity fluctation;
ϵ, dissipation energy;
$K_g a$, gas liquid mass transfer coefficient, gram-mol/sec./cu. meter/bar;
$K_l a$, liquid-liquid mass transfer coefficient, hour^{-1}
k_s, liquid-solid mass transfer coefficient, (hour-meter)$^{-1}$