Mixing has been defined as “the application of mechanical motion in order to create fluid dynamic effects that achieve a desired process result” [1]. The process result is the objective of the vessel operator and will be a transformation of the ingredients fed to the vessel into a product. The goal of the equipment supplier will be to understand the role of mixing in promoting the transformation and choosing an impeller that will create the appropriate fluid-dynamic effects to do this.

Processes carried out in stirred tanks can be generally divided into the following two classes:

- Those relying on flow generated by the impeller creating motion throughout the fluid, such as blending of pigments into a resin or emulsion in paint manufacture where homogeneity of the vessel contents is critical to product quality
- Those relying on “shear” to reduce the size of a second dispersed phase, whether gas bubbles, liquid droplets or particles, such as a hydrogenation reactor where smaller bubbles provide more surface area for mass transfer from the gas into the liquid phase

Impellers are often described qualitatively as, among others, high flow, high shear or high efficiency, and the choice of equipment required to achieve the process result most efficiently is made on this vague basis. This article describes how the performance characteristics of impellers commonly used in stirred tanks can be quantified, thereby enabling engineers to make educated decisions about which ones to use in order to achieve their desired process results.

**Turbulence**

Turbulent flow is characterized by the presence of random fluctuations in velocity, so-called eddies, that are superimposed on the mean, time-averaged flow. There will be a
range of eddy time and length scales associated with a particular flow field. The size of the largest eddies will be on the order of the size of the equipment generating the flow (for example, the blade width of an impeller). The size of the smallest eddies is the Kolmogorov length scale. The eddies also have a lifetime, with the larger eddies existing for a longer period than the small ones. Understanding the role turbulence plays in mixing processes is critical to successful design and scaleup [2].

Impeller geometries
There are four general classes of impellers used in stirred tanks operating in low to medium viscosity fluids in the turbulent regime (Re > $10^4$):

1. **Axial flow.** The primary flow generated by an axial-flow impeller is directed down toward the base of the vessel. Hydrofoils with narrow or wide blades are in this category. Hydrofoils have profiled blades that may be narrow like an airplane wing (Figure 1a) or wide like a marine propeller (Figure 1b). These impellers were developed to generate the same velocity profile as a propeller, but to be fabricated rather than cast to reduce the impeller’s weight and cost. They are also easier to install since they can be supplied as a hub and blades that are assembled inside the vessel [3]. These impellers are generally considered to be “low-shear” [4].

   An anti-ragging hydrofoil (Figure 1c) is used in wastewater applications. It has blades that are swept-back preventing build-up of fibrous matter, which is commonly present in municipal wastewater, on the leading edge of the blades.

2. **Mixed flow.** These impellers generate both axial and radial components of velocity and the distribution between the two can be controlled by adjusting the impeller diameter to vessel diameter ratio. Pitched-blade turbines (Figure 1d) are in this category. Pitched-blade turbines have flat blades that are usually angled at 45 deg, although shallower and steeper angles are sometimes used.

3. **Radial flow.** These impellers generate a strong radial component of velocity directed at the vessel wall. A pitched blade turbine with 90-deg blade angle generates radial flow and is commonly called a flat-blade turbine (Figure 1e).

   Impellers used for processes requiring dispersion of gas bubbles also generate a primarily radial flow, but have blades attached to a disk. The Rushton (Figure 1f) and Smith (Figure 1g) turbines are commonly used for these processes. The disk ensures that bubbles fed into the vessel beneath the impeller must flow through the blades where the local “shear” breaks them up, creating high interfacial area for mass transfer. The Rushton turbine is generally considered to be “high-shear” [4].

4. **High-speed dispersers.** These impellers look like circular-saw blades with alternating teeth angled up and down (Figure 1h). They operate at high rotational and tip speeds and are used almost exclusively for processes that require significant size reduction, such as dispersion and de-agglomeration of dry powder when preparing a slurry from liquid and a dry powder.

Hydraulic efficiency
Impellers in stirred tanks are machines that move fluid; essentially they are pumps. Like pumps, their efficiency can be defined and calculated. The hydraulic efficiency of a pump is the ratio of the kinetic energy of the flowing fluid to the mechanical energy input by the impeller.

The mechanical power input by an impeller in a stirred vessel is calculated from the following equation (Note: all nomenclature are defined in the box on p. 46):

$$P_{\text{MECH}} = P_o \cdot \rho \cdot N^3 \cdot D^5$$  \hspace{1cm} (1)
For axial-flow impellers, this is a disk with diameter equal to the impeller diameter and height equal to the blade width.

The primary flow generated by an impeller is calculated from Equation (2):

\[ Q = Fl \cdot N \cdot D^3 \]  \hspace{1cm} (2)

\( Fl \) is the impeller’s flow, or pumping number.

Both the power and flow numbers are measured experimentally and typical values for commonly used impellers are given in Table 1.

The average velocity in the impeller discharge can be calculated from Equation (3):

\[ \bar{U} = \frac{Q}{ADIS} \]  \hspace{1cm} (3)

\( ADIS \) is the area through which the primary flow is pumped.

For axial-flow impellers, this is a disk with diameter equal to the impeller diameter and for radial-flow impellers it is the wall of a cylinder with diameter equal to the impeller diameter and height equal to the blade width.

For axial-flow impellers:

\[ \bar{U} = \frac{Fl \cdot N \cdot D^3}{\left(\frac{\pi}{4}\right) \cdot D^2} = \frac{4Fl}{\pi} \cdot N \cdot D \]  \hspace{1cm} (4)

For radial-flow impellers:

\[ \bar{U} = \frac{Fl \cdot N \cdot D^3}{\pi \cdot w \cdot D} = \frac{Fl \cdot D}{\pi \cdot w} \cdot N \cdot D \]  \hspace{1cm} (5)

The energy dissipation rate, or power, of the flowing fluid is the product of the flowrate and the head that the pump develops:

\[ P_{HYDR} = Q \cdot \Delta H \]  \hspace{1cm} (6)

Where:

\[ \Delta H = \frac{\rho \cdot \bar{U}^2}{2} \]  \hspace{1cm} (7)

Combining Equations (2), (4), (6) and (7), for axial flow impellers:

\[ P_{HYDR} = Fl \cdot N \cdot D^3 \cdot \frac{\rho}{2} \left( \frac{4Fl}{\pi} \cdot N \cdot D \right)^2 = \frac{8Fl^3}{\pi^2} \cdot \rho \cdot N^3 \cdot D^5 \]  \hspace{1cm} (8)

\[ \phi_{AX} = \frac{P_{HYDR}}{P_{MECH}} = \frac{8}{\pi^2} \cdot \frac{Fl^3}{\rho \cdot N^3 \cdot D^5} = \frac{8}{\pi^2} \cdot \frac{Fl^3}{Po} \]  \hspace{1cm} (9)

Similarly, combining Equations (2), (5), (6) and (7), for radial-flow impellers:

\[ P_{HYDR} = Fl \cdot N \cdot D^3 \cdot \frac{\rho}{2} \left( \frac{Fl}{\pi w} \cdot N \cdot D \right)^2 \]  \hspace{1cm} (10)

\[ \phi_{RD} = \frac{P_{HYDR}}{P_{MECH}} = \frac{1}{2} \cdot \left( \frac{D}{w} \right)^2 \cdot \frac{Fl^3 \cdot \rho \cdot N^3 \cdot D^5}{Po \cdot \rho \cdot N^3 \cdot D^5} = \frac{1}{2 \pi^2} \cdot \left( \frac{D}{w} \right)^2 \cdot \frac{Fl^3}{Po} \]  \hspace{1cm} (11)

The hydraulic efficiency, \( \phi \), is plotted against the impellers’ power numbers in Figure 2. The circular symbols represent data measured by the FMP (Fluid Mixing Processes) consortium [5] using laser-Doppler anemometry and the diamonds represent data measured in the PMSL laboratory using particle-image velocimetry. The data are in agreement showing that measurement technique has no effect on the values of hydraulic efficiency calculated.

The hydrofoils are the most efficient impellers followed by the pitched-blade turbines, then the radial flow flat-blade and Rushton turbines. The high-shear disperser impeller is the least efficient, with a hydraulic efficiency of less than 1%. The difference in efficiency within a class of impellers is a result of the impeller to tank diameter ratio. A larger impeller is more efficient and this definition of hydraulic efficiency does not take this into account.

An alternative definition of efficiency has been proposed by Fort and others [6]. This is the mass of fluid pumped per unit of energy input by an impeller:

\[ \text{Efficiency} = \frac{m}{w} \]
\[ \eta_{\text{HYDR}} = \frac{\rho \cdot Q}{P_{\text{MECH}}} = \frac{\rho \cdot F_l \cdot N \cdot D^3}{P_{\text{M}} \cdot \rho \cdot N^3 \cdot D^3} = \frac{F_l}{P_{\text{M}} (N \cdot D)^2} \]  \hspace{1cm} (12)

This quantity has units of kilogram of fluid pumped per Joule of energy input by the impeller.

The power input per unit mass of fluid, for a vessel where depth is equal to vessel diameter, can be calculated from:

\[ \dot{\varepsilon} = \frac{P_{\text{M}} \cdot \rho \cdot N^3 \cdot D^3}{\left(\frac{\pi}{4}\right) \cdot \rho \cdot T^3} = \frac{4 \cdot P_{\text{M}} \cdot N^3 \cdot D^3}{\pi \cdot T^3} \]  \hspace{1cm} (13)

Re-arranging for impeller speed:

\[ N = \left( \frac{\pi \cdot \dot{\varepsilon} \cdot T^3}{4 \cdot P_{\text{M}} \cdot D^3} \right)^{\frac{1}{3}} \]  \hspace{1cm} (14)

Substituting Equation (14) into Equation (12) gives the following:

\[ \eta_{\text{HYDR}} = \frac{F_l}{P_{\text{M}} D^2} \cdot \left( \frac{\pi}{4} \cdot \frac{4 \cdot P_{\text{M}} D^3}{\dot{\varepsilon} \cdot T^3} \right)^{\frac{2}{3}} \]

\[ = 1.175 \cdot \frac{F_l}{P_{\text{M}} D^2} \cdot \left( \frac{D}{T} \right)^{\frac{4}{3}} \cdot \left( \frac{T}{\dot{\varepsilon}} \right)^{\frac{2}{3}} \]  \hspace{1cm} (15)

The hydraulic efficiency data plotted in Figure 2 are replotted in Figure 3 using the new definition from Equation (15) with a power per mass of 1 W/kg and vessel diameter of 1 m. The effect of impeller diameter is now taken into account and large diameter impellers (\(D/T \approx 0.3\)) are more efficient than smaller ones (\(D/T \approx 0.5\)) are more efficient than smaller ones (\(D/T = 0.3\)), pumping approximately twice the mass of fluid per unit of energy input.

### Shear

In any flowing system, the shear rate is the time-averaged velocity gradient [7].

Oldsheue [3] has compared the time-averaged velocity gradients in the discharge of a hydrofoil and pitched-blade and Rushton turbines to show that the Rushton generates higher shear than the pitched-blade, which generates higher shear than the hydrofoil. This has become the conventional wisdom in the mixing field.

Figure 4 shows the mean velocity profiles for a hydrofoil (in green) and pitched-blade turbine (in red), which were measured using particle-image velocimetry in the PMSL laboratory. The dashed lines show the average velocity gradient in the discharge. Figure 5 shows the mean velocity profile for the Rushton turbine and, again, the dashed lines show the average velocity gradient in the discharge. The shear rate is described by the following equation:

\[ \dot{\gamma} = \frac{v_H - v_L}{r_H - r_L} \]  \hspace{1cm} (16)

where \(v_H\) and \(v_L\) are the high and low velocities in the gradient and \(r_H\) and \(r_L\) are the radial positions corresponding to the locations where these velocities were measured. Since the velocities are normalized by the impeller tip speed and the radial positions by the impeller radius, Equation (16) can be re-written as follows:

\[ \dot{\gamma} = \frac{(\alpha - \beta) \cdot V_{\text{TIP}}}{(\psi - \omega) \cdot R} = \frac{\Lambda}{R} \cdot \frac{V_{\text{TIP}}}{R} \]  \hspace{1cm} (17)

Values of \(\alpha, \beta, \psi, \omega\) and \(\Lambda\) are given in Table 2. Also the ratio of \(\Lambda/\Lambda_{\text{HYDFL}}\) is shown and, at equal tip speed and impeller diameter the Rushton generates the highest shear rate followed by the pitched-blade turbine and then the hydrofoil.

Engineers are concerned with the power drawn by the impeller since this determines the size of the agitator needed to achieve the desired process result. Equation (13) can be rearranged to express the power input by the impeller per unit mass of fluid in terms of tip speed:

\[ \dot{\varepsilon} = \frac{4}{\pi^4} \cdot \frac{P_{\text{M}} \cdot V_{\text{TIP}}^3}{T} \cdot \left( \frac{D}{T} \right)^2 \]  \hspace{1cm} (18)

The \(n^3\) term must be introduced because \(V_{\text{TIP}} = \pi ND\). Comparing different impellers of equal diameter at the same scale:

\[ V_{\text{TIP}} \propto P_{\text{M}}^{-1/3} \]  \hspace{1cm} (19)

Comparing any impeller with the hydrofoil:

\[ \frac{\dot{\gamma}_{\text{IMP}}}{\dot{\gamma}_{\text{HYDFL}}} = \frac{\Lambda_{\text{IMP}}}{\Lambda_{\text{HYDFL}}} \cdot \frac{V_{\text{IMP}}}{V_{\text{HYDFL}}} \]  \hspace{1cm} (20)

Substituting Equation (19) into Equation (20):

\[ \dot{\gamma}_{\text{IMP}} = \dot{\gamma}_{\text{HYDFL}} \cdot \left( \frac{P_{\text{M}} \cdot V_{\text{TIP}}^3}{P_{\text{M}} \cdot V_{\text{TIP}}^3} \right)^{1/3} \]  \hspace{1cm} (21)
EXPERIENCE THE EVENT FOR PROCESSING TECHNOLOGY

2017 CHEM SHOW
OCT 31 - NOV 2 • JAVITS CENTER • NEW YORK

▶ 300+ EXHIBITING COMPANIES
▶ 5,000+ CPI PROFESSIONALS
▶ 30+ FREE SEMINARS
▶ HUNDREDS OF NEW PRODUCTS

DESIGNED FOR PROCESS ENGINEERS, PRODUCTION & PLANT PERSONNEL, EXECUTIVES AND R&D

For over 100 years, the Chem Show continues to connect leading manufacturers of equipment, systems and services for the CPI with tens of thousands of professionals from every segment of the process industries.

FREE REGISTRATION AT CHEMSHOW.COM
FREE SEMINAR PROGRAM

TUESDAY

Benefits of IIoT Monitoring of Pumps, Valves, Equipment and Document Management  ➔ Flowrox

Optimizing Process Design Using Pneumatic Conveying and Blending  ➔ FLSmidth Inc.

Innovative Mechanical Seal Technologies for Industries to Operate More Reliably and Efficiently with Less Downtime and Maintenance Costs  ➔ SCENIC PRECISE ELEMENT INC.

Powder Characterization for Process Optimization  ➔ Freeman Technology Inc.

Increase Reliability and Reduce Energy Costs with Pump & Piping Analysis Using Flow Modeling Software  ➔ Hydraulic Institute

Bulk Storage and Day’s-Use Product Management  ➔ Steelcraft

Solutions to Ensure Successful Scale-up for Process Intensification  ➔ Fuji Techno Industries Corporation

Troubleshooting Common Bulk Solids Handling Issues  ➔ Jenike & Johanson, Inc.

Solving Challenges for Ultra Low Flow Fluid Handling  ➔ Bronkhorst USA Inc.

Ultrasonic Processing from Benchtop to Industrial Production: Applications, Process Intensification & Scale-up  ➔ Hielscher Ultrasonics GmbH

Minimizing Nozzle Loads and Pipe Stresses to Optimize Chemical Pumping Systems  ➔ Hydraulic Institute

Methods to Avoid Caking and Unwanted Agglomeration  ➔ Jenike & Johanson, Inc.

2018 Chemical Industry Spending Outlook: USA & Canada  ➔ Industrial Information Resources, Inc.

Solutions to Clean Out Your Thermal Oil System  ➔ Multitherm

WEDNESDAY

Methods for Testing Flowmeter Calibration: Multivariable Transmitters  ➔ Beamex

Maximize Reliability for Rotary Positive Displacement Pumps in the Chemical Processing Industry  ➔ Viking Pump, Inc., A Unit of IDEX Corporation

Advanced-Flow Reactors: Made for Industrial Production  ➔ Corning SAS

Solutions for Combustible and Fugitive Dust for Compliance & Safety  ➔ SonicAire

The Kirkpatrick Awards - Innovative Chemical Engineering Technologies that Have Been Commercialized in the Past Two Years  ➔ Chemical Engineering Magazine

Transitioning to Continuous Pressure and Vacuum Filtration Technologies from Batch Operations  ➔ BHS - Sonthofen Inc.

Choosing Appropriate Chemical Splash Protective Clothing  ➔ Lac-Mac Limited

Induce and Enhance Phase Transfer Catalysis with Ultrasounds  ➔ Hielscher Ultrasonics GmbH

Leveraging Your Expertise to be a Chemical Industry Consultant  ➔ Association of Consulting Chemists & Chemical Engineers, Inc.


Navigating Pitfalls When Choosing Pressure Relief Devices for System Designs  ➔ BS&B Safety Systems, L.L.C.

THURSDAY

Using an Anti-fouling Membrane Filtration System for Higher Concentration  ➔ BKT

Advances in Particle Size Analysis in the Lab and Online  ➔ Particle Sizing Systems


Tips to Communicate Effectively with the Petrochemical Industry Today and Tomorrow  ➔ Hydrocarbon Processing

Boost the Efficiency of Shift Handovers and Morning Meetings at Your Plant  ➔ eschbach GmbH

Industry Trends in Control Valve Automation  ➔ Badger Meter

Agitation Selection and Sizing for Viscous Products  ➔ Steelcraft

FREE REGISTRATION AT CHEMSHOW.COM

PARTNERS

MEDIA

† 300+ EXHIBITING COMPANIES

† 30+ FREE SEMINARS

† Solids Handling Issues

† Product Management

† Bulk Storage and Day’s-Use

† Jenike & Johanson, Inc.

† Hydraulic Institute

† Jenike & Johanson, Inc.

† Fuji Techno Industries Corporation

† Freeman Technology Inc.

† Chemical Engineering Technologies

† The Kirkpatrick Awards - Innovative Chemical Engineering Technologies that Have Been Commercialized in the Past Two Years

† Chemical Engineering Magazine

† BKT

† BHS - Sonthofen Inc.

† Chemical Industry Consultant

† Leveraging Your Expertise to be a Chemical Industry Consultant

† Industrial Information Resources, Inc.

† Viking Pump, Inc., A Unit of IDEX Corporation

† Chemical Engineering Technologies

† Hielscher Ultrasonics GmbH

† BS&B Safety Systems, L.L.C.

† Seminar Descriptions and Times, Go to CHEMSHOW.COM

YOU CAN RESERVE A SEAT FOR THE SEMINARS YOU WISH TO ATTEND WHEN YOU REGISTER FOR THE SHOW.

TO REGISTER FOR THE SHOW, AND FOR SEMINAR DESCRIPTIONS AND TIMES, GO TO CHEMSHOW.COM.
Table 2 also shows the ratio of the shear rates when the impellers operate at equal power input per mass. Taking power numbers from Table 1, the ranking of the impellers does not change. Therefore, whether compared at equal tip speed or power input the Rushton turbine generates the highest shear rate followed by the pitched-blade turbine then the hydrofoil. This ranking can be tested against a process result that is dependent on shear, namely the break-up of droplets to create a liquid-liquid dispersion.

**Process result**

Mass transfer between two immiscible liquid phases, with or without reaction, is an important process result. The interfacial area available for mass transfer is proportional to the volume fraction of the dispersed phase and inversely proportional to the Sauter mean droplet size. The process result is given by the following equation. Grenville and others [12] have shown that for impellers with blades:

\[
\frac{k_{\text{MAX}}}{V_{\text{TIP}}^2} = 0.104 \cdot Po^{1/2}
\]

Where \( V_{\text{TIP}} = \pi N D \).

The standard deviation for this correlation is \( \pm 10\% \).

The maximum energy dissipation rate within the vortex is given by the following equation [13]:

\[
\epsilon_{\text{MAX}} = A \cdot \frac{k_{\text{MAX}}^{3/2}}{l_0}
\]

\( l_0 \) is a length scale related to the flow near the impeller and it is a fraction of the impeller diameter. Substituting Equation (22) into Equation (23) and setting \( l_0 = D/x \) and \( A = 1 \):

\[
\epsilon_{\text{MAX}} = 1.04 \cdot x \cdot Po^{3/4} \cdot N^3 \cdot D^2
\]

The standard deviation for this correlation is \( \pm 15\% \).

Where measurements have been made, typical values of \( x \) are given in Table 1. Generally, the scale of the trailing vortex for the Rushton and pitched-blade turbines is equal to one-half of the projected height of the blade at its tip. For hydrofoils the scale of the trailing vortex is equal to the projected height of the blade at its tip.

Equations (13) and (24) can be combined to show that the ratio of the maximum energy dissipation rate to the average power input per mass, \( K \), is:

![Figure 4. This graph shows a plot of the mean velocity profiles for pitched-blade turbine and hydrofoil impellers.](image)
The ratio is weakly dependent on the type of impeller ($Po$), dependent on the scale of the vortex ($x$) and strongly dependent on the size of the impeller ($D/T$). The reason for this is that a small-diameter impeller must operate at a higher tip speed than a larger one to input the same power and the maximum kinetic energy is proportional to the tip speed squared.

The droplet size data plotted versus the average power input per mass in Figure 6 are replotted in Figure 7 versus the maximum energy dissipation rate in the trailing vortex. The variations in the trailing vortex energy dissipation rate generated by the impellers and the effects on the droplet size are now correctly accounted for, including the high-shear disperser.

The conventional wisdom in the mixing industry has been that hydrofoil impellers generate “low shear” and Rushton turbines generate “high shear” [3, 4] and this is true if only the time-averaged velocity gradients are compared. The maximum kinetic energy dissipation rate within the trailing vortex, $\varepsilon_{\text{MAX}}$, generates the stresses that break-up droplets, or any other second phase, in an agitated vessel. Rather than describing these impellers as “high shear,” it is more rigorous to call them “high dissipation” or “high stress.”

**Applications**

There are many processes in which the fluid dynamic effect that achieves the process result is commonly considered to be “shear” although, strictly, the process result is determined by the maximum energy dissipation rate within the trailing vortex. One example of a “shear” driven process is flocculation of fine particles. Agitators are designed to provide a desired shear rate, or G-value. G is defined as:

$$G = \left( \frac{P}{\mu \cdot V} \right)^{1/2} = \left( \frac{Po \cdot N^3 \cdot D^5}{\mu \cdot V} \right)^{1/2}$$  \hspace{1cm} (26)

This shear rate is based on the vessel-averaged power input per volume and the fluid’s dynamic viscosity. Equation (26) suggests that, provided that the average power per volume is kept constant, the same G-value will be generated and the flocculation performance will be the same. Benz [14] has written a review of the problems that will be encountered taking this approach to agitator design, especially the fact that it takes no account of impeller type or diameter. He concludes that “G-value has no legitimate use in designing or specifying agitators.”

Spicer and others [75] have measured the size and structure of flocculated polystyrene particles using a hydrofoil, pitched blade and Rushton turbines at G-values, as defined in Equation (26), of 15, 25 and 50 s$^{-1}$. The corresponding values of vessel-averaged power input per mass are $2.25 \times 10^{-4}$, $6.25 \times 10^{-4}$ and $2.50 \times 10^{-3}$ W/kg. Grenville and Spicer [76] have re-analyzed these data and the floc length versus the maximum kinetic energy dissipation rate, calculated using Equation (23), is plotted in Figure 8. This approach to the analysis correlates the data and suggests that the concept of a G-value should work for agitator design provided that it is based on the maximum energy-dissipation rate in the trailing vortex — not the vessel averaged power per volume.

The selectivity of competitive reactions carried out in semi-batch mode is determined by the local mixing rate [17], the micro-mixing rate, in the region where the added reactant is introduced to the vessel [18]. Bourne and Dell’ava [19] have shown that the selectivity of an azo-coupling reaction can be maximized by feeding the added reactant at the impeller where the trailing-vortex energy dissipation rate determines the rate of micro-mixing. They, and Nienow and others [20], have also shown that, provided the feed location is geometrically similar, the selectivity of the reaction can be maintained on scale-up if the trailing-vortex energy dissipation rate is the same at the two scales. This has also been shown to apply to precipitation reactions where the particle size and morphology need to be controlled [21, 22].
Finally, mixing in crystallization processes requires both rapid local mixing to minimize primary nucleation and high flow to promote homogeneity, favoring secondary nucleation and crystal growth. Also, a balance between crystal growth and crystal damage must be considered in choosing the appropriate impeller [23].

Conclusions
Mixing processes can be described in terms of the desired process result. Generally this result will be controlled by the flow and turbulence intensity generated by an impeller. The approach described here can be used to determine which the best impeller to achieve this result will be. It can also be used to translate laboratory and pilot-scale results taken with one type of impeller to a larger scale using a different geometry, provided that the process result and controlling dynamic effect can be identified.

The term high-shear is commonly used to describe an impeller’s capability for dispersion of a second immiscible phase generating surface area for mass transfer. Similarly, low-shear is used to describe impellers that, in multi-phase processes, allow the second phase to grow, and flocculation is a good example of this.

In a turbulent agitated vessel, the time-averaged velocity gradients are of little use, and potentially misleading, for comparison of impeller performance and agitator design. While the term “shear” is used qualitatively to describe impellers’ dispersing capabilities, it must be recognized that the true mechanism of break-up is determined by the maximum energy dissipation rate within the impellers’ trailing vortices. This understanding enables engineers to select the appropriate impellers for their processes.

References
1. Etchells III, A. W., Lecture notes, CHEG 615 Special Topics in Mixing, University of Delaware.
10. www.youtube.com/watch?v=VKY4hS3p2Ac
11. www.youtube.com/watch?v=ZlU4PrnUE151c

Authors

Richard K. Grenville is director of Mixing Technology at Philadelphia Mixing Solutions Ltd. (1221 East Main Street, Palmyra PA 17078; Phone +1-717-202-7976; Email: rkgrenville@philamixers.com) and has worked in the field of mixing for over 30 years including 22 years as a consultant for DuPont Engineering. He is an adjunct professor at Rowan University and the University of Delaware, where he co-teaches courses on mixing and regularly presents seminars to customers and for AIChE Student and Local chapters. Grenville has a B.Sc. in chemical engineering from the University of Nottingham and a Ph.D. from Cranfield Institute of Technology. He is a Chartered Engineer, Fellow of the IChemE, Member of the AIChE and is currently serving as president of the North American Mixing Forum (NAMF). He has co-authored several papers and conference presentations on various aspects of mixing including jet mixing, mixing of non-Newtonian fluids, solids suspension and education.

Jason Giacomelli is a research and development engineer at Philadelphia Mixing Solutions Ltd. (1221 East Main Street, Palmyra PA 17078; Phone +1-717-832-8884, jgiacomelli@philamixers.com) where he is responsible for running pilot-scale experimental programs for both internal product development and process development on behalf of customers. He also runs computational fluid dynamic (CFD) models to support these programs. He is a member of AIChE and works with the local chapter to help with community outreach programs, such as the Science Technology Engineering and Math (STEM) Festival in Washington, D.C. Giacomelli has a B.S.Ch.E. from Rowan University and is currently studying for a Ph.D. on the subject of solids suspension in stirred vessels with professor Harry van den Akker at the University of Limerick in Ireland. He has co-authored a number of papers and conference presentations.

Gustavo Padron is a senior technical consultant on industrial fluid mixing at BHR Group (The Fluid Engineering Centre, Cranfield, Bedfordshire, U.K., Phone: +44-3301-191-775; Email: gpadron@bhrgroup.co.uk). He currently manages the Fluid Mixing Processes (FMP) industrial research consortium at BHR Group, which has been running continuously for more than 30 years, and has 20 years of experience in fluid mixing. He has co-authored several technical publications and has given presentations at international conferences on fluid mixing and nanoparticle dispersion. Padron holds a bachelor’s degree from the Universidad Metropolitana, Venezuela, a master’s degree and a Ph.D. from the University of Maryland, College Park, all in chemical engineering.

For additional articles on mixing and other unit operations, go to the Chemical Engineering archives at www.chemengonline.com.