Mixing in the process industry:

- Chemicals
- Food
- Pharmaceuticals
- Paper
- Polymers
- Minerals
- Environmental

Chemical Industry:

- Paints and Coatings
- Synthetic Rubbers and Resin
- Sealants and Adhesives
- Food, Juice, Oils, and Candy
- Catalysts
- Acids
- Biofuels, Ethanol
- Pharmaceuticals

Importance of Mixing[1]

Chemical Industry: Up to $10 Billion lost because of poor mixing
Pharmaceutical Industry:

1. Low yield $100 million
2. Poor scale-up $500 million
3. Lost opportunity form poor mixing – very large number

Typical Mixing Problems adopted from R. K. Grenville:
Single-phase:
Determine the time required to blend miscible liquids to obtain a uniform mixture

1. Reduce concentration gradients
2. The miscible fluids may have different physical properties
3. A chemical reaction may be present

Two-phase: Liquid-liquid
Determine the power required to from 0.01 mm droplets of oil in water.

1. Generate surface area for mass transfer / reaction
2. Stable dispersion (emulsion) may be final product

Two-phase: Gas-liquid

Determine the rate of mass transfer that can be obtained from sparging gas into liquid within a mechanically agitated tank. Assume geometry, power and fluid properties are given.

1. The gas phase will from small bubbles with a high surface area per unit volume of gas.
2. The purpose of the high surface area maybe to give high mass transfer rates and ultimately high reaction rates in the liquid phase.
3. Another purpose maybe to form a stable dispersion (foam) may be final product.

Two-phase: Solid-liquid

Determine the minimum impeller speed that will just suspend all of the particles in the tank. Given the diameter and physical properties of the particle and fluid, tank geometry and power.

1. Dissolving / Precipitation / Crystallization
2. Catalyst particles.
3. High solids loading - pastes.

Three-phase:

Determine the reaction rate within a liquid in which the catalyst particles are solids and one of the reactants is a gas that dissolves into the liquid to react with a second reactant. Given reaction rate, power, particle and fluid properties, particle diameter, tank geometry.

Mixing Definition:

Mixing is the reduction of inhomogeneity in order to achieve a desired process result.
Inhomogeneity: concentration, phase, temperature.
Process results: increase mass and/or heat transfer, reaction rate, or product properties.

Typical Tank Dimensions

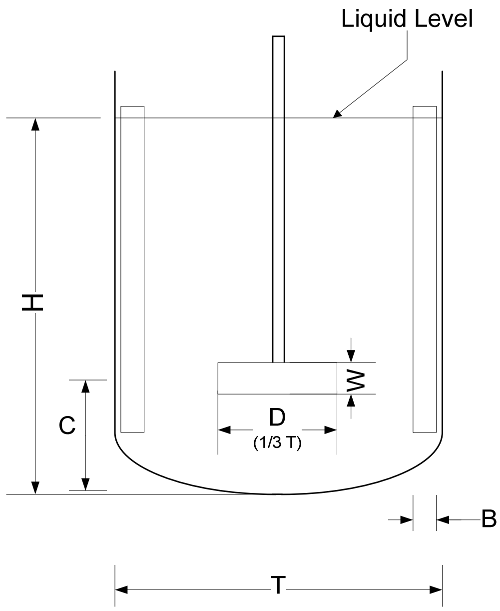

Figure 1: Definition of Tank Dimensions

Importance of Baffles: See video from Visual Mixing[2]

Types of Tanks with mixers

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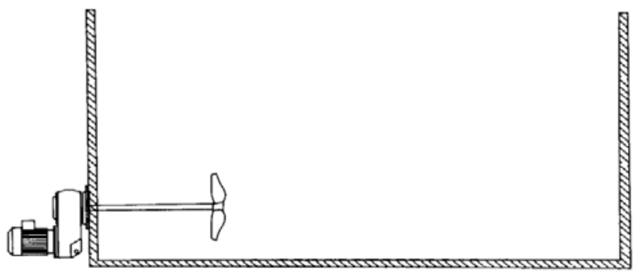


Figure 6-3 Side-entering mixer for large product storage and blending tanks.

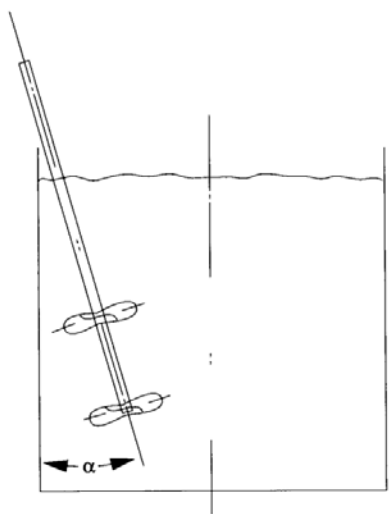


Figure 6-4 Angular top-entering mixer for small tanks with portable mixers.

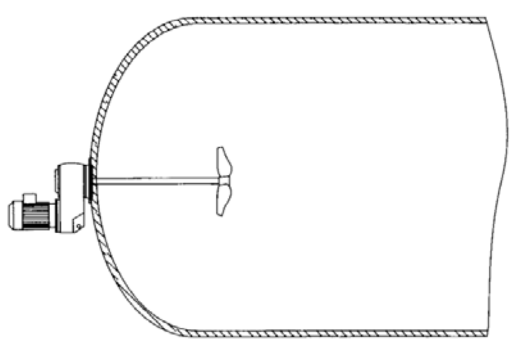


Figure 6-5 Side-entering mixer for horizontal cylindrical vessel.

Figure 2: Alternative Mixing Configurations[3]

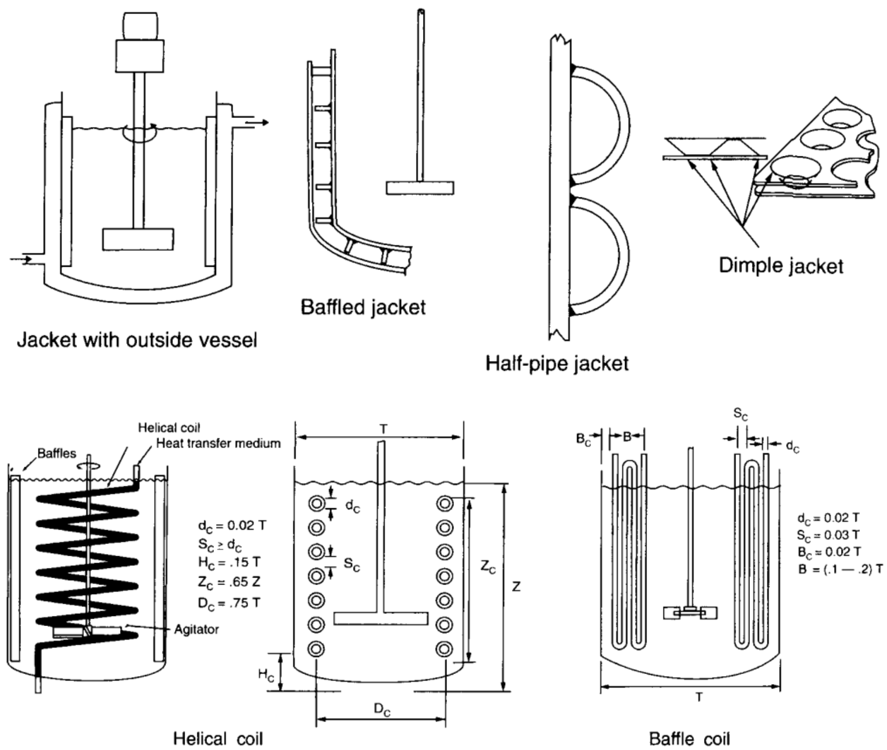


Figure 3: Heat Transfer Surfaces[3]

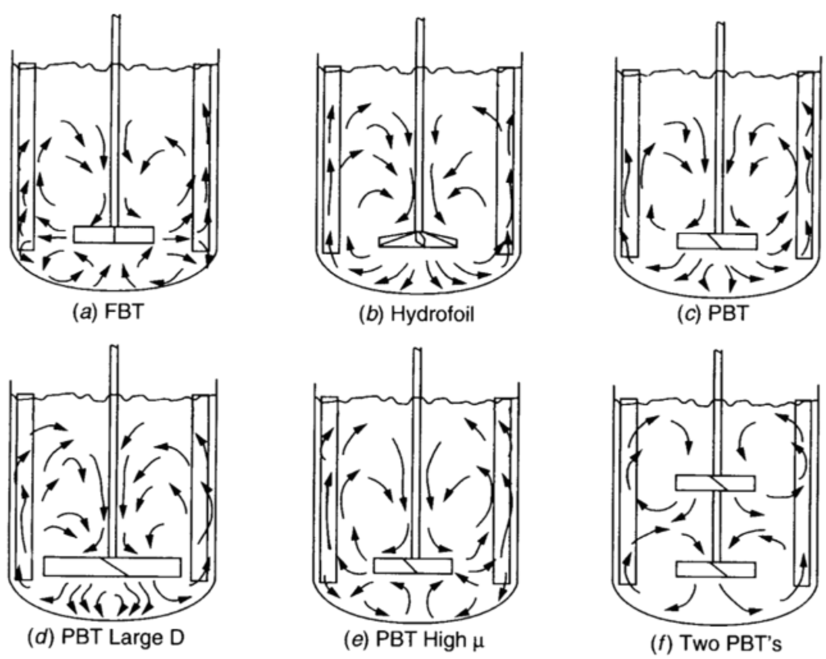
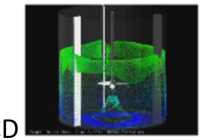


Figure 4: Fluid flow patterns with different impellers, diameters and liquid viscocity. PBT: Pitched Blade Turbine, FBT: Flat Bladed Turbine.[3]

Show Axial Flow CFD simulation from the Visual Mixing CD  Axial flow looks like this

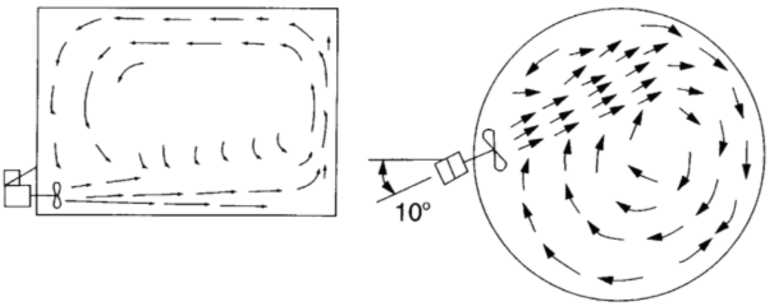


Figure 5: Flow patterns for a side - entering Propeller Mixer[3]

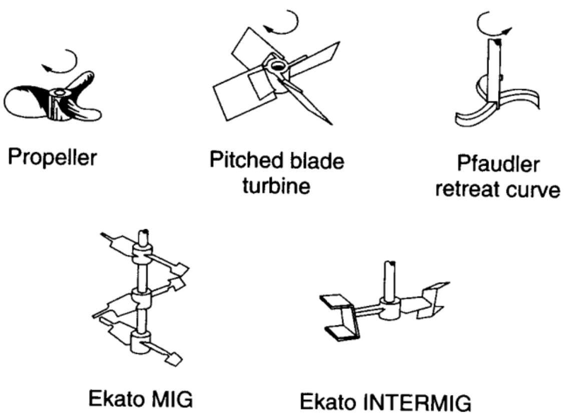


Figure 6: Axial Flow Impellers[3]

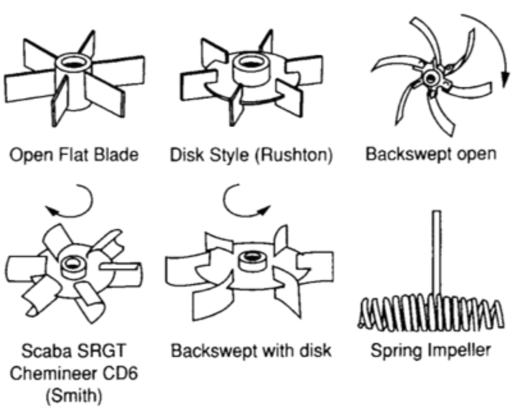


Figure 7: Radial Flow Impellers[3]

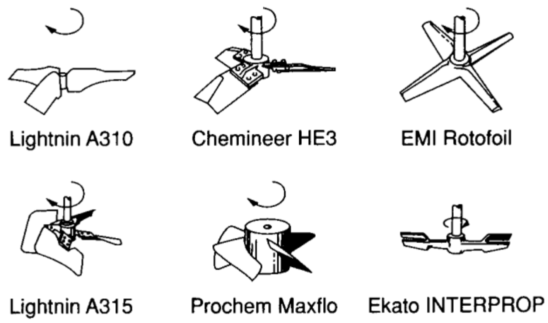


Figure 8: Hydrofoil impellers[3]

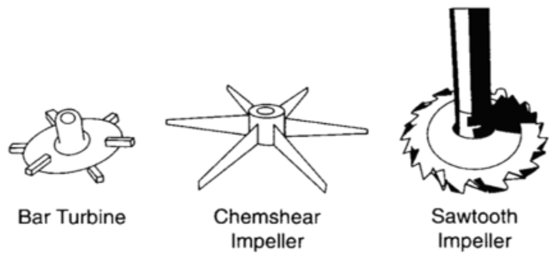


Figure 9: High-Shear impellers[3]

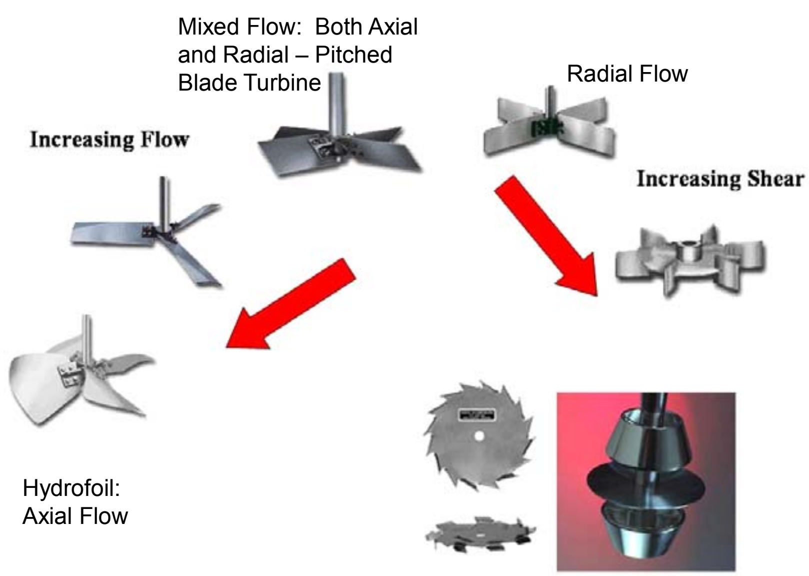


Figure 10: From R. K. Grenville, Mixing Notes

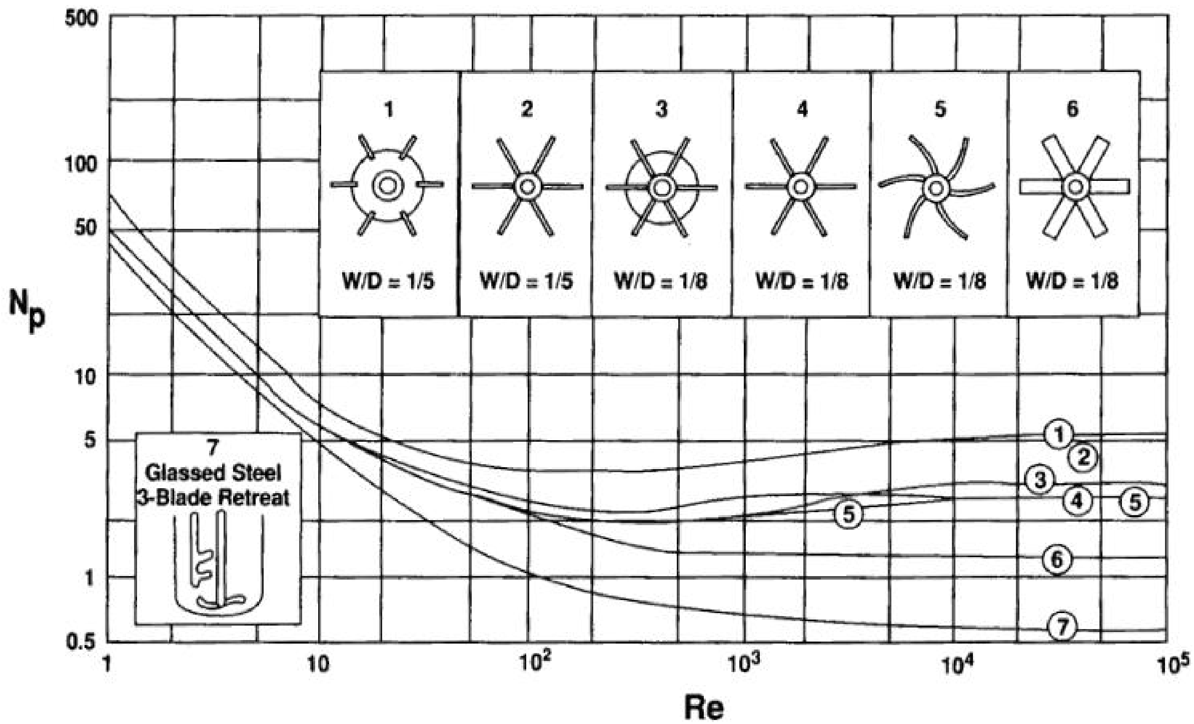


Figure 11: Power Number Plot similar to Figure 19.3, except that the Glassed Steel 3-Blade retreat Impeller is given as curve 7.[1] Under a Reynolds number of 100 these impellers shown above should not be used for mixing. Curve 1 is a Rushton Turbine. Curves 2 & 4 are Open Flat Blades. Curve 5 is a Backswept open Impeller. Curve 6 is a Pitched Blade Turbine (PBT). .

Impeller Characteristics:

Reynolds Number for tank

$$Re = \frac{inertial}{viscous} = \frac{\rho(v)^2}{\mu \frac{v}{D}} = \frac{\rho(ND)^2}{\mu \frac{ND}{D}} = \frac{\rho N D^2}{\mu} \quad (1)$$

Where $N[=]Revolutions/s$, $D[=]m$ is the impeller diameter, and ρ & μ are the density and viscosity of the fluid, respectively.

Power

$$Power\ Number = N_P = \frac{P_O}{\rho N^3 D^5} \quad (2)$$

The power number is a function of the impeller, blade width, number of blades, blade angle, D/T, baffle configuration and impeller elevation.

Torque

$$Torque = P_O/(2\pi N) \quad (3)$$

Impellers can be too big or too small

The D/T, or impeller diameter to tank diameter ratio, can dramatically affect an impellers' effectiveness.

With a particularly small D/T ratio, the impeller is unable to create a strong flow in the vessel. As the D/T ratio gets larger, the impeller becomes more able to create an adequate flow pattern. However, if the D/T is too large, there is not enough space between the impeller and the vessel walls to allow a strong axial flow and the mixing efficiency decreases.

Here, we see 3 videos of pitched blade turbines with different D/T ratios but equal power consumption. Note the differences in flow created by the impellers.

D/T = 0.17 D/T =0.38 D/T =0.67

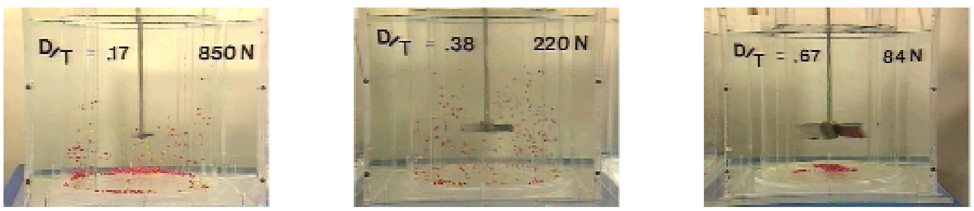


Figure 12: Demonstration of Effect of Impeller Diameter and Speed on Fluid flow pattern

Table 1: Equivalent Power Example

D/T	N	N_P	P_O
0.17	850		
0.38	220		
0.67	84		

Validate that the equivalent power can be obtained with the following impellers shown in Table 1. Assume that each of these impellers are placed in a tank filled with water and that each tank has a Diameter of 1 m.

Comparison of impellers based on equal power and torque

In these clips, 3 common impellers are compared at equal torque and equal power consumption by varying the impeller diameter and holding N constant.

The impellers are the Rushton turbine, the pitched-blade turbine and the Lightnin A310. Note that here the conditions are chosen so the differences are emphasized; see the clip "Impellers can be too big or too small" to see the effect of diameter on performance. See the comparison of the A310 and PBT at high solids loading for another veiw of solids suspension.

Rushton D/T=0.23 | PBT D/T=0.31 | A310 D/T=0.42

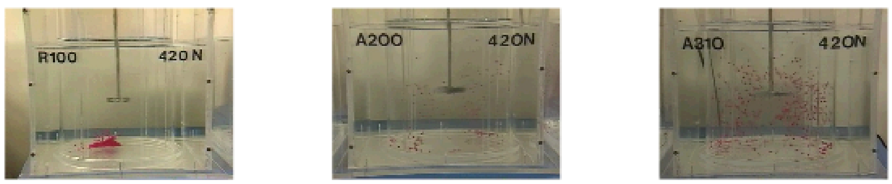


Figure 13: Comparison of 3 impellers at a low solids loading

Table 2: Equivalent Power Example

Impeller Type	N_P	D/T	N	P_O
Rushton		0.23	420	
Pitched Blade Turbine (PBT)		0.31	420	
A310		0.42	420	

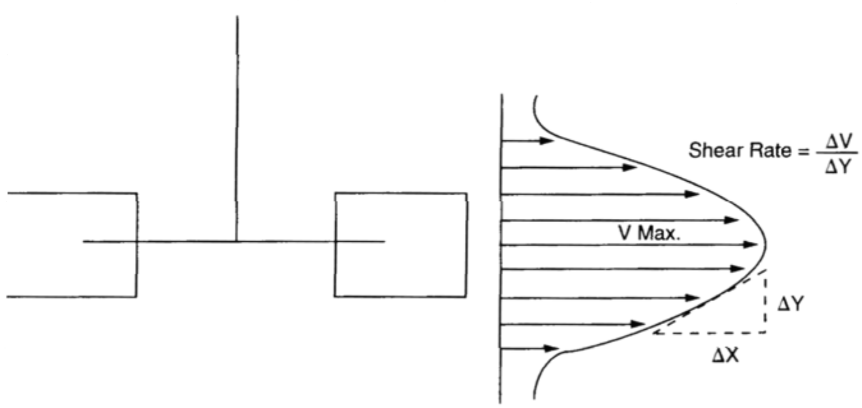


Figure 14: Velocity profile of a Radial Flow Blade as a function of height at the blade tip[3]

Determination of Process Conditions for Desired Result

As a result of the complex nature of mixing operations, many design calculations are performed using correlations. In many cases part of the design process is validated using a small laboratory scale system. After adjustments are made to the process then it must be scaled up to full production size. This is typically performed in steps of scale starting from laboratory to pilot plant to full scale. These laboratory experiments can either be performed in house or at a mixing company such as Philadelphia Mixing Solutions[4]. Correlations are useful to design these experiments and in some cases to scale-up directly to full scale.

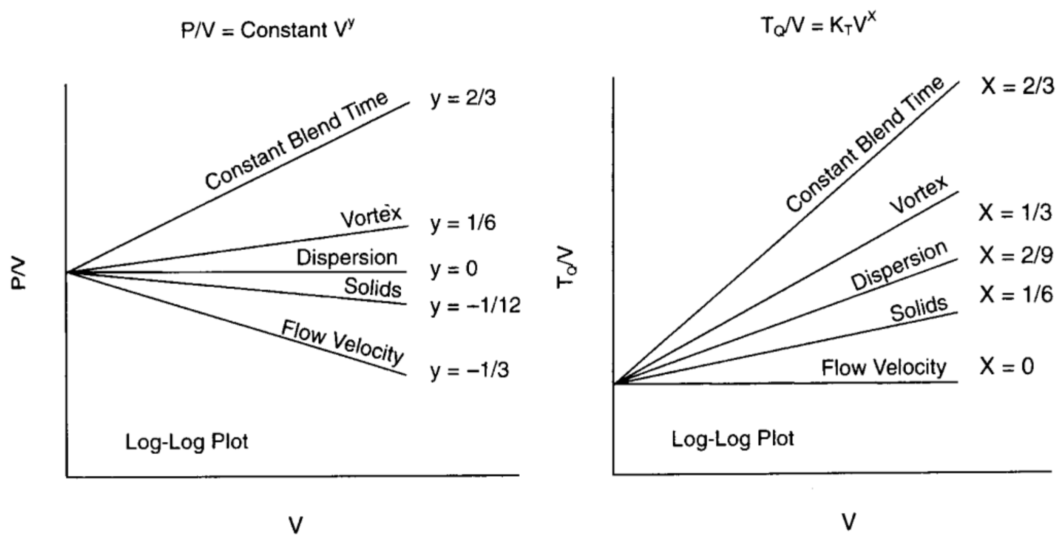


Figure 15: Scale-up Methods for Mixing Operations[3]

Power per unit Volume and Torque per unit volume relationships are given in Figure 15. Power was given previously as

$$Power = P_O = N_P \rho N^3 D^5$$

$$Torque = P_O/(2\pi N) = N_P \rho N^2 D^5/(2\pi) \quad (4)$$

$$Flow \propto vArea = NDD^2 = N_{flow} N D^3 \quad (5)$$

Example values for N_{flow} are:

Table 3: Dimensionless Flow Numbers, N_{flow}[5]

Impeller	Characteristic	N_{flow}
Propeller	Pitch = D	0.5
6 Blade Turbine with disk	W/D=1/5	0.75
6 Blade Turbine with disk	W/D=1/8	0.5
Pitched Blade Turbine	W/D=1/5	0.75

Pitch is the theoretical distance a prop moves forward in one revolution

Power per unit volume can be obtained from

$$\frac{P_O}{V} = \frac{N_P \rho N^3 D^5}{\frac{\pi}{4} T^2 H} \tag{6}$$

Since for a typical tank geometry $T = H$ and $D = T/2 \; or \; T/4$ then the power per unit volume can be related to only the impeller speed and diameter

$$\frac{P_O}{V} \propto \frac{N^3 D^5}{D^2 D} = N^3 D^2 \tag{7}$$

Blend Time Example from R. K. Grenville

Objective: Determine a universal blend time correlation? By measuring in regions of differing "mixing intensity

1) Performed in "standard" geometry vessels:
   a) T = 2, 6 and 9 feet
   b) V = 40, 1100 and 3800 gallons
   c) Geometrically identical at all three scales
2) Test various impeller types.
3) Range of fluid properties:
   a) Viscosity
   b) Newtonian and non-Newtonian
4) Tracer added to liquid surface.
5) Measurement Technique: Conductivity
6) Three probes in regions of different mixing intensity:
   i) 1 - Under Impeller
   ii) 2 - Between Shaft and Wall
   iii) 3 - Behind Baffle

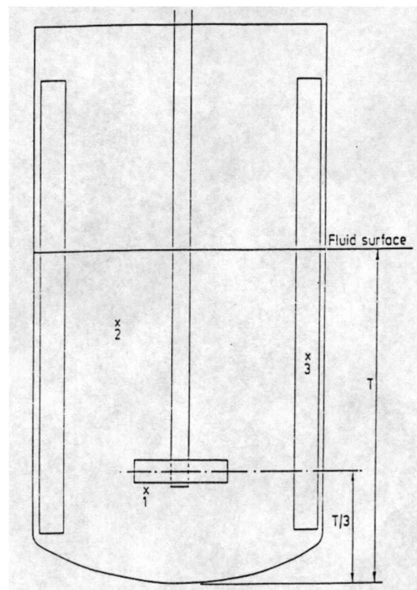
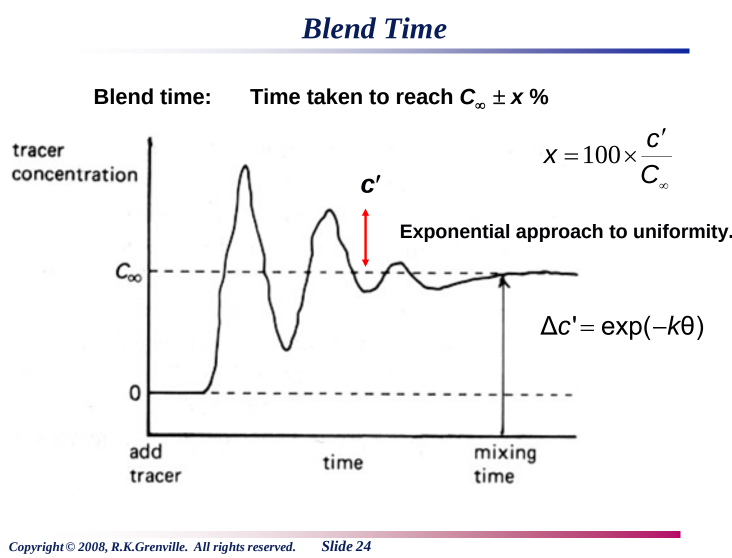


Figure 16: Grenville Bend time experiment



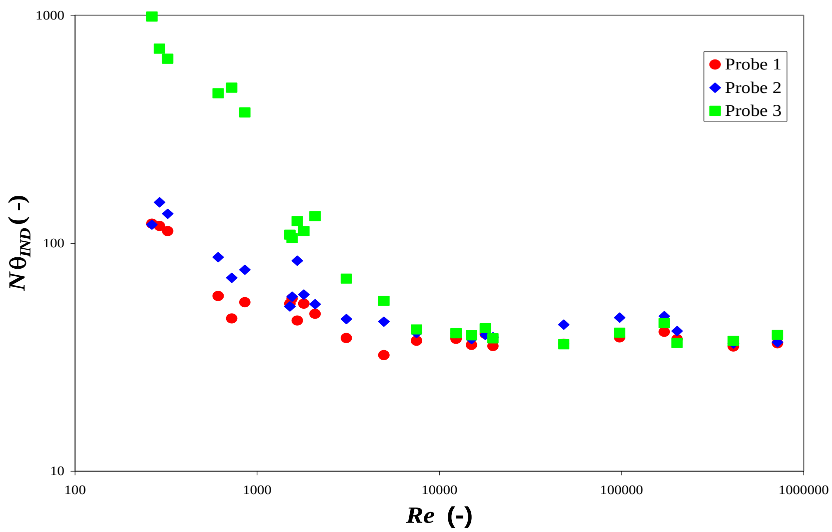


Figure 17: Results of Studies, Where θ is the blending time.

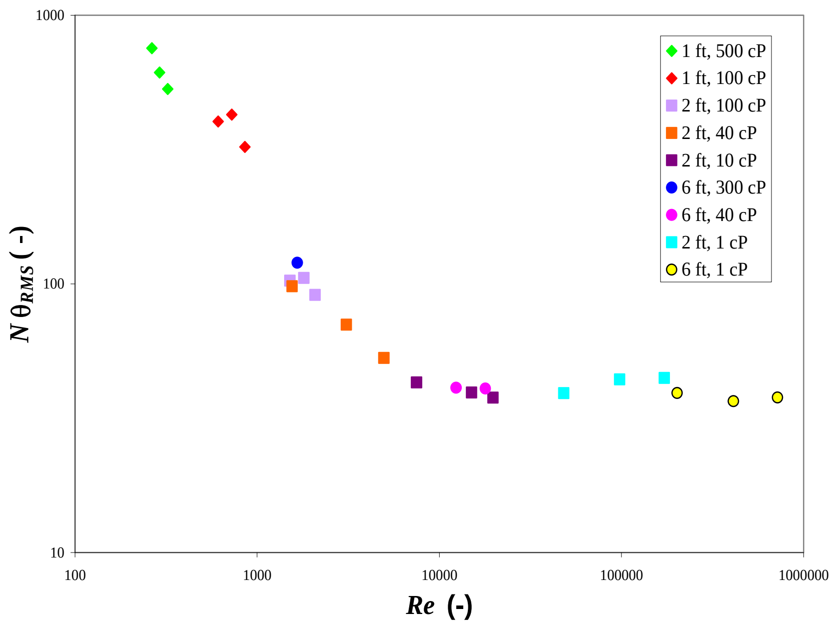


Figure 18: Results used for Correlation based on Baffle location measurements. θ is blend time.

Grenville[6],[7] gives the blend time to achieve within 5% of the desired concentration as:

$$Blend\ time_{95\%} = \frac{5.40}{N_P^{1/3} N} \left(\frac{T}{D}\right)^2$$

This correlation if for turbulent Reynold's numbers > 10,000 and a liquid depth equal to the vessel diameter, T.

Calculate the required blend time for the following tank:

Pitched blade turbine

Impeller Diameter: 1 m

Operating speed: 84 RPM

Fluid: Water

Tank Diameter = 3.0 m

Tank Volume = 5600 gallons

1. Calculate Reynolds Number
2. Calculate blend time for within 5% of desired value
3. Design a blending tank for a volume of 10,000 gallons assuming T=H and D=T/3 and dimensions scaled with volume
    a. Constant speed
    b. equal power per unit volume
    c. assuming power per unit volume based on Figure 15.

Give the power required, the tank and impeller dimensions and impeller speed.

---

[1] Paul, E. D. V. A. Atiemo-Obeng, and S. M. Kresta, "Introduction of the Handbook of Industrial Mixing", Wiley, 2004.

[2] Visual Mixing CD by S. Kresta and K. Boyle included with the text by Paul, E. D. V. A. Atiemo-Obeng, and S. M. Kresta, "Handbook of Industrial Mixing", Wiley, 2004

[3] Hemrajani, R. R., G. B. Tatterson, "Mechanically Stirred Vessels," Chapter 6 of Paul, E. D. V. A. Atiemo-Obeng, and S. M. Kresta, "Introduction of the Handbook of Industrial Mixing", Wiley, 2004

[4] Philadelphia Mixing Solutions, http://www.philamixers.com/index_eng.asp. Lab testing information at http://www.philamixers.com/index_eng.asp?page=labtesting

[5] Geankoplis, C. J., Transport Processes and Unit Operations, 3rd Ed. Prentice Hall PTR, Englewood Cliffs, New Jersey 1993. Page151. (This contains a good section on mixing and scale-up)

[6] Grenville, R. K. "Blending of viscous Newtonian and pseudo-plastic fluids, Ph.D. dissertation, Cranfield Institute of Technology, Cranfield, Bedfordshire, England (1992) and personal communication.

[7] Grenville, R. K., A. W. Nienow, "Blending of Miscible Liquids," Chapter 9 of Paul, E. D. V. A. Atiemo-Obeng, and S. M. Kresta, "Introduction of the Handbook of Industrial Mixing", Wiley, 2004