A FLUID-MIXING LABORATORY FOR ChE UNDERGRADUATES

Gabriel Ascanio, Robert Legros, Philippe A. Tanguy
Ecole Polytechnique • Montreal, Quebec, Canada H3C 3A7

Mixing is a common operation in the process industries and is generally performed by a rotating impeller in a vessel. Products obtained from food, petroleum, mining, pharmaceutical, pulp and paper, and chemical industries would not be available without fluid mixing equipment and technology. Mixing also plays a vital role in industrial waste treatment and in environmental cleaning, such as in sulfur dioxide absorption for treatment of acid rain.[1,2]

A wide range of mixing situations can be found in practice, which may involve high- or low-viscosity fluids, suspending solids in liquids, dispersing gas or solids in liquids, etc. Mixing operations at the industrial level are increasingly carried out at low to moderate Reynolds numbers, leading to segregated or dead regions and resulting in long mixing times. The simplest way used to improve mixing efficiency consists of increasing the rotational speed, which unfortunately leads to higher energy consumption. Mixing times in small-scale stirred tanks are commonly measured by non-intrusive techniques such as colorimetry. This technique also allows observation of the aforementioned segregated regions and how they tend to disappear as the impeller speed increases.

The objective of the mixing laboratory is to give students practical experience in the fluid mechanics of mixing by analyzing power consumption and mixing times associated with radial and axial flow impellers with Newtonian and non-Newtonian fluids.

The mixing laboratory is part of an undergraduate unit operations course offered by the Department of Chemical Engineering at Ecole Polytechnique of Montreal for senior-year students. Groups composed of a maximum of three students perform the required laboratory work in a period of four hours. The group prepares a preliminary report after finishing the experiments, and the students either hand over a full report or give an oral presentation the following week. Both the full reports and the oral presentations consist of a description of the experiment's objectives, its theoretical basis, the engineering method used, the experimental setup, and the operating conditions. Then they present the experimental data, discuss the results, and make recommendations to improve the laboratory.

EXPERIMENTAL SETUP

The mixing system used in all the experiments is a modified Turbotest (VMI Rayneri) laboratory mixer, shown in Figure 1. It consists of a transparent polycarbonate vessel of 165-mm inner diameter and 230-mm height, with an open top fixed to a rigid table for safe operation. Two classical impellers are tested—a radial-flow impeller (6-blade Rushton turbine) and an axial-flow impeller (marine propeller). The impellers are mounted on a rigid shaft driven by a DC motor, with the speed carefully regulated in a range from 10 to 2500 rpm by means of a DC controller. The motor is mounted on a rigid structure that can be moved to adjust the vertical posi-

***Gabriel Ascanio** received his BS and MS from the National University of Mexico in 1988 and 1995, respectively, and his PhD from Ecole Polytechnique of Montreal in 2003. He is currently a postdoctoral fellow at URPEI in the Department of Chemical Engineering. Some of his research interests are in coating processes and mixing of rheology complex fluids.*
***Robert Legros** is Professor of Chemical Engineering at Ecole Polytechnique of Montreal. He received his BS from Ecole Polytechnique in 1983 and his PhD from the University of Surrey in 1987. His academic research involves solids thermal treatments in fluid beds, modeling of combustion reactors, heat and mass transfer, and hydrodynamics of spouted beds. Some of his current research interests are related to pharmaceutical engineering, namely in powder technology and downstream processes.*
***Philippe A. Tanguy** is Professor of Chemical Engineering at Ecole Polytechnique of Montreal. He received his BSc in 1976 and his Doctorat de spécialité in 1979, both from Université de Paris, and his PhD from Laval University in 1982. His research interests are in non-Newtonian fluid mechanics, CFD and process engineering involving complex fluids, in particular coating processes, and in agitation and mixing operations.*

The purpose of this experiment consists of determining the mixing time with two impellers providing different flow patterns. The mixing time, defined as the time needed to reach a specified degree of homogeneity, can be determined by various techniques . . .

tion of the impeller. As can be seen in Figure 1, a standard mixing configuration is used as a starting point, with the impeller placed on the vessel centerline at 1/3 of the liquid height. The agitation torque is measured by a non-contact type torquemeter (range between 0.1 and 1.42 N.m) fitted between the motor and the agitation shaft.

Newtonian fluids consist of aqueous solutions of corn syrup having a viscosity of 1.5 Pa.s, while aqueous solutions of carboxy methyl cellulose (CMC) are employed as non-Newtonian fluids. The mixing times are measured with a colored tracer consisting of Methylene Blue diluted in both solutions. The two solutions, together with the tracer, are prepared prior to the experiments and allowed to settle at least 24 hours in order to eliminate air bubbles. The rheological properties of the fluids are determined by a Bohlin Visco 88V viscometer using a concentric cylinder configuration. Rheological measurements and the experiments are performed at room temperature (around 24°C).

The cost of the laboratory mixer and the solutions used for the experiments is about \$5,000 and \$20, respectively.

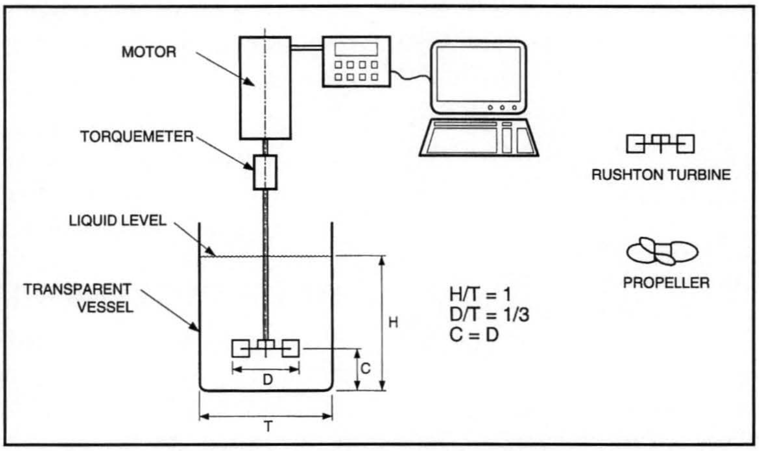

Figure 1. *Experimental setup.*

EXPERIMENTS

Power Consumption

This experiment consists of determining the power consumption for both radial- and axial-flow impellers with Newtonian fluids. For that purpose, the fluid under study must be added to the H level of the tank (see Figure 1) and then the mixer speed is set to zero rpm and the torquemeter to zero N.m. The impeller speed is gradually changed from 15 to 700 rpm, and the torque reading for each speed is used to calculate the power consumption by means of

$$P = 2\,\pi r N T \tag{1}$$

where r is the impeller radius in m, N is the rotational speed in rps, and T is the torque in N.m.

The power consumption is correlated to the impeller speed by means of the dimensionless power number (Np) and the Reynolds number (Re), defined by

$$Np = \frac{P}{\rho N^3 D^5} \qquad \text{and} \qquad Re = \frac{\rho N D^2}{\mu} \tag{2}$$

where P is the power in Watts, ρ is the fluid density in kg/m^3, D is the impeller diameter in m, and μ is the dynamic viscosity in Pa.s.

The laminar and transition regimes must be identified after plotting Np as a function of Re on a log-log scale;[3,4] the constant K_p for each impeller can be calculated by

$$K_p = Np\,Re \tag{3}$$

Mixing Times

The purpose of this experiment consists of determining the mixing time with two impellers providing different flow patterns. The mixing time, defined as the time needed to reach a specified degree of homogeneity, can be determined by various techniques based on the measurements of concentration, density, electrical conductivity, temperature, or by colorimetry, optical methods, thermal method, etc. The colorimetry technique is a qualitative method to determine the mixing time by adding a small amount of a color tracer to the fluid that is being mixed. The overall fluid color will change, and mixing time corresponds to the time when the tracer is judged to have completely dispersed within the fluid. The detailed procedure for measuring the mixing time is

1. Use the configuration shown in Figure 1 with the Rushton turbine.
2. Add fluid (aqueous corn syrup or aqueous CMC) up to the H level.
3. Prepare the color tracer solution by dissolving 10 mL of Methylene Blue in 100 mL of fluid to be studied.
4. With the mixer at rest, add 15 mL of the color tracer solution to the tank containing the fluid.
5. Set impeller speed at 100 rpm and switch the mixer on.
6. Measure the mixing time at this speed.
7. Repeat Steps 3 to 5, using different speeds. The speed range

for this experiment is from 100 rpm to 600 rpm, with increments of 100 rpm.

8. Repeat the experiment for the marine propeller.

As proposed by Moo-Young, *et al.*,[5] mixing time can be correlated with the impeller speed by means of a dimensionless mixing time defined as

$$Nt_m = \alpha(Re)^{\beta} \tag{4}$$

where t_m is the mixing time in s, N is the impeller speed in rps, Re is the Reynolds number, and α and β are adjustable parameters.

Shear Rate of non-Newtonian Fluids

The purpose of this experiment is to find out the effective shear rate for non-Newtonian fluids in the vicinity of the impeller by the Metzner-Otto correlation.[6] They developed a general relationship to correlate the impeller speed and the shear rate of a non-Newtonian fluid in the laminar regime. Based on the single knowledge of the power curve for Newtonian fluids, this relationship can be used to interpret and correlate power draw data for non-Newtonian fluids. This method assumes that there exists an average mixer shear rate developed in the vicinity of the impeller, which corresponds to the power consumption. This shear rate is directly proportional to the impeller speed through

$$\dot{\gamma}_A = k_s N \tag{5}$$

where k_s is the mixer shear rate constant.

The average shear rate, $\dot{\gamma}_A$, defines an apparent viscosity, which is used in the definition of the Reynolds number for power consumption prediction for non-Newtonian fluids. The apparent viscosity is determined from viscometric measurements at the appropriate shear rate and used directly for plotting the power curve. The determination of the average shear rate, $\dot{\gamma}_A$, involves the following steps (see Figure 2):

1. For a given impeller speed, a power number (Np') is calculated from the P vs. N for non-Newtonian fluids.

2. Using this power number, Np', a Reynolds number (Re') is obtained from the power number-Reynolds number correlation for Newtonian fluids.

3. Finally, the average shear rate can be determined from the viscometric data and, using the impeller speed, the mixer shear rate constant, k_s, can be calculated from Eq. (5).

The procedure for this experiment consists of the following manipulations:

1. Mount the Rushton turbine at the end of the shaft and locate it in the center of the vessel, as in the first experiment.
2. Add the aqueous CMC to the H level.
3. Gradually change the speed, record the torque for each speed, and calculate the impeller power consumption from Eq. (1).
4. Plot the power consumption (P) vs. impeller speed (N).
5. By using the viscometer with the same fluid, record the apparent viscosity for each shear rate and plot the μ_A vs. $\dot{\gamma}_A$ curve.
6. Following the steps mentioned above, determine the average shear and calculate the mixer shear rate constant k_s from the Metzner-Otto correlation (Eq. 5).
7. Repeat the experiment using the propeller.

FULL REPORT AND ORAL PRESENTATION

As mentioned before, students are asked to prepare a preliminary report after finishing the experimental work. A week later they must deliver a full report or give an oral presentation. The full reports must contain

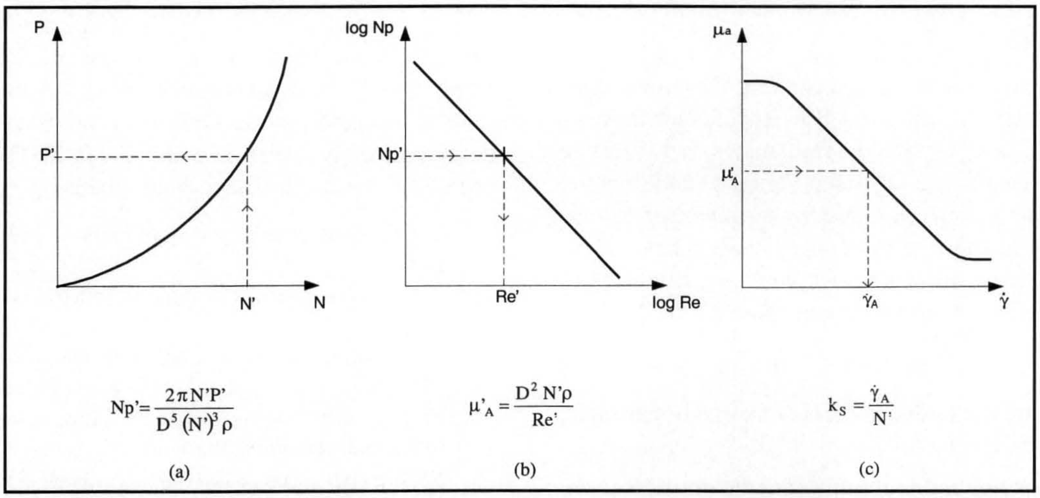

Figure 2. *Determination of the shear rate constant k_s: **a)** non-Newtonian power consumption, **b)** Newtonian power consumption, **c)** non-Newtonian viscometry.*

- ►*An abstract,* including the objectives, the methodology used to achieve the objectives, and results and conclusions in relation to the proposed objectives.
- ►The *objectives* must be clearly stated.
- ►*A theoretical perspective* different from the one presented in the laboratory manual.
- ►*Main results for discussion and analysis, including graphs and tables.* An example of a set of experimental data obtained by students is shown in Figures 3 and 4. The power curves in terms of the dimensionless power number (Np) as a function of the Reynolds number (Re) are shown in Figure 3. After performing linear regression with the experimental data, a good correlation can be observed between Np and Re. It must be noted that a slope of -1 should be obtained between Np and Re corresponding to the laminar region. An error of 5.47% and 0.53% in the slope is obtained for the Rushton turbine and the propeller, respectively. Figure 4 shows the dimensionless mixing time as a function of the Reynolds number for both impellers with a Newtonian fluid. From the linear regression results, it can be observed that the larger coefficients α and β correspond to the Rushton turbine, which is in good agreement with the results reported in the literature.[2]

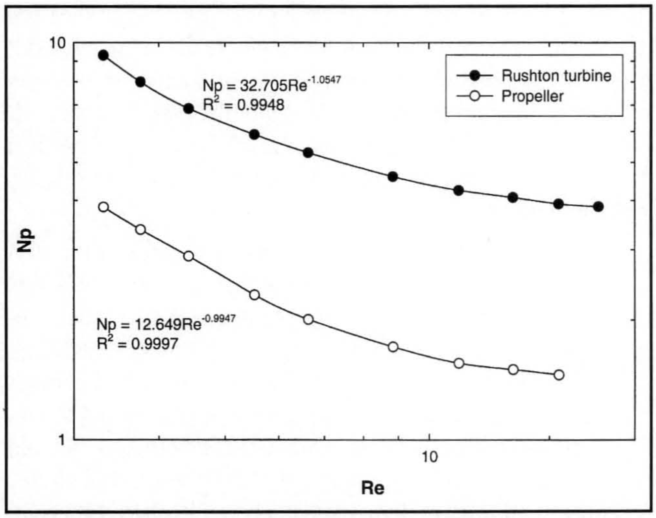

Figure 3. *Experimental power curves for the Rushton turbine and the propeller.*

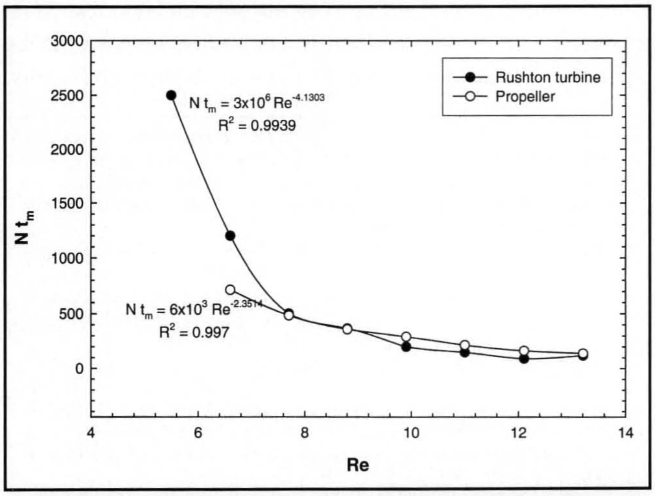

Figure 4. *Dimensionless mixing time as a function of the Reynolds number for Newtonian fluids.*

- ►*Interpretation, analysis, and discussion.* These elements should be presented in great detail in a quantitative way, including the experimental error encountered. In the case of the experiments of power consumption and shear rate of non-Newtonian fluids, the torque should be measured at least three times in order to determine the experimental error.
- ►*Recommendations.* This feature is used as feedback channel, so the students should suggest another experiment to perform or modifications to the experimental setup in order to improve the experiments.
- ►*Appendix.* All the raw data must be presented so the reviewer can verify if the data were well processed.

On the other hand, the oral presentation is evaluated in terms of the form and the content. The introduction and objectives, presentation structure, illustrations, conclusions, and questions are all considered in the form. The subject knowledge, theoretical basis, and references and analysis capability are considered as parts of the presentation.

CONCLUSION

Because mixing is a unit operation involved in many industrial applications, a good understanding of this operation is central for a successful process. The proposed experiments give the students a general introduction to the fluid mechanics of mixing with Newtonian and non-Newtonian fluids, using impellers that provide different types of flow. In fluid mixing technology, as in other process design areas, dimensionless groups are used to correlate scale-up parameters. For that reason, experimental results must be presented in terms of these dimensionless numbers to be useful to the process designers. The proposed mixing experiments enable engineering students to gain excellent insight into the use of dimensionless groups.

REFERENCES

1. Coulson, J.M., J.F. Richardson, J.R. Backhurst, and J.H. Harker, *Chemical Engineering,* Vol. 1, Pergamon Press, p. 225 (1990)
2. Harnby, N., M.F. Edwards, and A.W. Nienow, *Mixing in the Process Industries,* 2nd ed., Butterworth Heinemann (1992)
3. Rushton, J.H., "The Use of Pilot Plant Mixing data," *Chem. Eng. Prog.,* **47**, No. 9, p. 485 (1951)
4. Rushton, J.H., E.W. Costich, and H.J. Everett, "Power Characteristics of Mixing Impellers, Part 1." *Chem. Eng. Prog.,* **46**, No 8. p. 395 (1950)
5. Moo-Young, M., K. Tichar, and F.A.L. Dullien, "The Blending Efficiencies of Some Impellers in Batch Mixing," *AIChE J.,* **54**, 139 (1976)
6. Metzner, A.B., and R.E. Otto, "Agitation of Non-Newtonian Fluids," *AIChE J.,* **3**(1), 3 (1957) ❒