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CBE 140A: Fluid Mixing

1 Introduction

One of the most commonly made assumptions in your chemical engineering career thus far is likely the one least critically examined—assume well-mixed. As an example, consider what would happen if a reactor is not of uniform composition or temperature. Instead of answering this difficult question (often covered in graduate coursework), it might be simpler to determine how much more agitation is needed to adequately mix its contents. This experiment will provide opportunity to characterize mixing in several different ways.

2 Objective

The experimental equipment provided includes a cylindrical, transparent acrylic tank of water, agitated by a motor driving a shaft that can be equipped with many types of straight-blade impellers, a turbine, and a propeller. In addition, a removable set of baffles may be installed in the tank. The impact of stirring speed, type of impeller, liquid level, and inclusion of baffles will be observed through the qualitative mixing behavior, the power consumed by mixing, and the time to mix salt homogeneously throughout the water.

3 Theory

Summaries of relevant mixing theories are provided in Chapter 9 of [1] and starting on page 6-34 of [2]. Most methods of predicting mixing behavior make use of empirically-derived correlations of dimensionless groups. The relevant numbers are the impeller Reynolds number Re, power number N_P, Froude number Fr, and blending time number, to be defined later:

$$Re = \frac{\rho N D^2}{\mu} \qquad N_P = \frac{P}{\rho N^3 D^5} \qquad Fr = \frac{DN^2}{g} \tag{1}$$

where ρ = fluid density,
D = impeller diameter,
N = impeller rotational speed in revolutions per minute,
μ = fluid viscosity,
P = mixing power, and
g = gravitational acceleration.

The relationship between Re and N_P has been demonstrated to be highly dependent on the tank and impeller geometry: the size of the impeller relative to the tank, the relative height of the impeller in the fluid, the angle and type of the impeller blades, the number of blades, the position and angle of the impeller in the tank, the presence and relative size of baffles, and so on. However, if all these sources of variability are controlled, the dimensionless numbers defined above can be correlated. See Figures 9.13 in [1] and 6-40 in [2] for examples. Generally, starting at low Reynolds numbers and increasing from 1 to 1,000, the power number will decrease by one or two orders of magnitude, occasionally experience a slight increase, and finally reach a constant value beyond a Reynolds number of roughly 10^4. Inclusion of baffles typically result in a larger power number at the same Reynolds number.

A dimensionless blending time number can be calculated as the product of the blending time t_b (with units) and N, the rotational speed. The relationship between t_bN and the Reynolds number is displayed in Figure 9.16 of [1]. The general behavior to expect is a decreasing blending time number until the Reynolds number is increased beyond 10^4, at which point the dimensionless number will become constant. Baffles generally decrease the mixing time.

Let's review some physics for calculation of empirical power consumption. Recall that torque is the product of a force and the distance from the axis of rotation at which the force is measured: $T = Fd$. The power consumed by a continuously rotating object is the product of the torque and angular speed, $P = T\omega$. Note that in this equation ω is the angular speed in units of radians (not revolutions) per unit time.

When considering how to design a large tank mixer based on characterization of a smaller but otherwise identical system, there are several methods to scale up the process. All options are based on holding a different parameter constant upon scale-up, usually a dimensionless group. The least feasible method would be maintaining constant blending time, as it likely leads to prohibitively expensive power consumption. Another method is maintaining constant impeller tip speed, ND. The process can be scaled up by holding the Reynolds or Froude number constant. A more common approach is to hold the mixing power per unit volume of liquid constant, which results in the following, with subscripts denoting the larger or smaller tank:

$$\frac{N_2}{N_1} = \left(\frac{D_1}{D_2}\right)^{\frac{2}{3}} \tag{2}$$

4 Experimental Apparatus

Figure 1 illustrates the major equipment used to study fluid mixing. A cylindrical tank of water (1) is mixed by an impeller (2) turned by an electric motor (3). The tank has baffles (4) that can be easily added or removed. The motor rotational speed is displayed for instantaneous measurement (5). An optical tachometer is available for confirmation of rotational speed measurement. The motor speed can be controlled with the knob (7) and turned on or off with the switch (6). The motor sits on a freely rotating arm—any force exerted on the fluid to mix it results in an equal force on the motor in the opposite direction. A wire connects the motor-arm assembly to a Vernier Bluetooth-enabled dynamometer, which measures force. If connected to a computer, the appropriate software can automatically log force data periodically over time. The tank can be filled and drained through a hose and ball valve (9). A Vernier conductivity sensor (10), affixed to a ring stand (not shown), can be submerged in the water for periodic, automatic recording of conductivity. A large assortment of impellers are available, but not shown here: a turbine, propeller, and many sizes of rectangular straight-blade impellers.

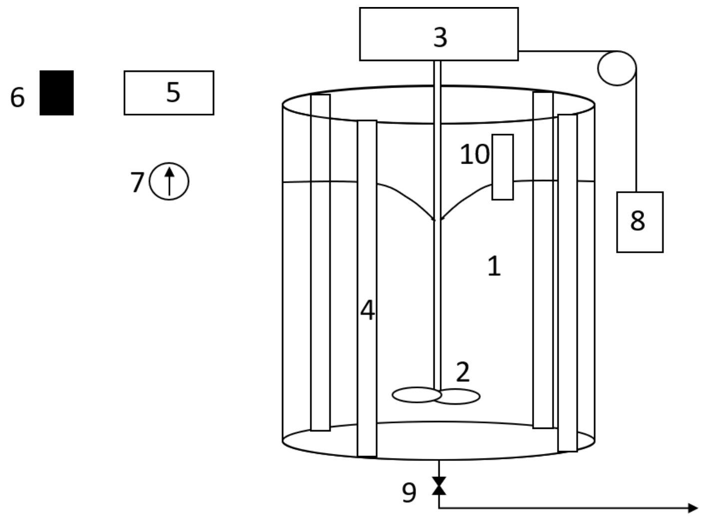

Figure 1: Experiment 10: fluid mixing apparatus.

5 Safety

The major hazards associated with this experiment are the following: The motor, powered from an electrical outlet, introduces the risk of injury from electric shock. Avoid by ensuring the power cord is not wetted or touched when in operation. Through accumulation of biological contaminants in the water, there is also a risk of infection. Contact the instructional staff if you believe the tubing needs cleaned or replaced. If water splashes out of the apparatus, there are risks to clothing damage, slips, and falls. Avoid this by carefully considering the impact of opening or closing of valves prior to acting, and clean spills immediately if they do occur. The rotating motor shaft could pose a risk of injury; avoid this by securing potentially loose hair, clothing, etc. This list is only a starting point and not intended to be fully comprehensive—please keep the safety of yourself and others in mind throughout the laboratory sessions.

6 Experimental Procedure

Begin the experiment by filling the tank, starting by connecting the drain tubing to a water faucet. With the drain valve open, allow flow into the tank until a water depth of 0.3 meters. When filled, close the faucet valve, followed by the drain ball valve. If baffles are installed, remove them from the tank—to do this, first disconnect the wire connected to the dynamometer and lift the motor assembly out of the tank, carefully place on its side atop the bench. While the motor is out, remove the current impellers and install the propeller at the end of the shaft. Place the motor assembly back on the tank and reset the wire from the dynamometer on the motor arm. Set the mixing speed to 50 RPM, allowing the system to reach steady state. Observe and record the mixing pattern—addition of small airsoft pellets and food dye can aid in visualizing the flow. Set up the computer software such that power is being periodically recorded, and ensure measurements are taken at steady state. Begin recording conductivity from the Vernier probe, securely positioned in the water, at a frequency of 10 samples per second. Add 25 grams of salt (sodium or potassium chloride will both work) at a position opposite the probe and wait for the conductivity to stabilize. Repeat this process at faster rotational speeds increasing by, for example, 50 RPM each time, until the water level nears the tank rim. Beads can be removed at any time if they disrupt other measurements with a net. The water can be drained and the tank refilled if the food dye or salt concentration becomes too high.

Repeat this series of trials for different types, sizes, angles, and heights of impellers, and with baffles included and excluded.

Note: If you wish to ensure the final conductivity of the mixed salt solution corresponds to the appropriate concentration, you will need to create a calibration curve by measuring the conductivities of several prepared standard solutions of known salt concentrations, e.g., 0, 0.25, 0.50, 0.75, and 1.00 molar.

7 Data Analysis

Characterize the mixing of water for each series of trials conducted by: plotting power and mixing time as a function of rotational speed, as well as power number versus Reynolds number. Describe the flow pattern observed, and any variations in these patterns as the mixing speed increased. Compare these charts and patterns to their expected behaviors—if there is disagreement, what might be the cause, and is there evidence for it?

For the data you were able to collect, investigate the effect of baffle inclusion and impeller type, size, angle, and height on the relationship between power and rotational speed, mixing time and rotational speed, and power number as a function of Reynolds number. Note this is combinatorial, allowing several methods of analysis. Comment on significant results. Do they agree with the predicted relationships between these parameters? If not, what might be the cause, and is there evidence for it?

Suppose the data collected in this experiment is to be used to design a geometrically similar scaled-up mixer with a volume of 1,000 liters of solution with physical properties similar to water. How will you scale up this process? What would you recommend as the larger tank impeller's rotational speed and power consumption?

References

[1] Julian Smith, Warren McCabe, and Peter Harriott. *Unit operations of chemical engineering.* McGraw-Hill, seventh edition, October 2005.

[2] Don W. Green, editor. *Perry's chemical engineers' handbook.* McGraw-Hill, eighth edition, 2008.