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Mixing in the chemical engineering curriculum

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He studied Chemical Engineering at the University of Nottingham in the UK, graduating in 1983, and started work as an Applications Engineer for Chemineer.

He then went to work at the Fluid Mixing Processes consortium, which is managed by the British Hydromechanics Research Group, as a Project Engineer. His main area of research was mixing of non-Newtonian fluids. He also registered as a graduate student at Cranfield Institute of Technology and received his PhD in 1992.

He then joined DuPont as a mixing consultant in the Engineering department working on a wide variety of projects including the Cellulosic Ethanol plant which is under construction in Nevada, Iowa.

In 2013 he joined Philadelphia Mixing Solutions as Director of Mixing Technology.

He co-teaches courses on mixing at Rowan University in New Jersey and at the University of Delaware and is a Chartered Engineer and a Fellow of the Institution of Chemical Engineers.

He was recently elected as the vice-president of the North American Mixing Forum and will become president in 2016.

Mixing in the Chemical Engineering Curriculum

Introduction

Mixing is a crucial operation in the process industries yet it is rarely covered in the chemical engineering curriculum. Smith[1] estimated that, in 1990, the US chemical industry lost approximately $10 billion a year due to poorly designed or operated mixing processes. Reasons include lower yield in competitive reactions, longer than expected batch times on scale-up and poor understanding of the impact of complex fluid rheology on mixer design all of which may delay commercialization.

Little has changed since Smith's paper was published yet, given the recognized importance of mixing as a discipline, it may be surprising that few universities offer a formal course on the subject.

There are a number of organizations offering continuing education courses on mixing and this should be taken as an indication of its importance to the chemical industry. These include the Center for Professional Advancement, the American Institute of Chemical Engineers and the British Hydromechanics Research Group. Also a number of larger companies employing mixing specialists offer in-house training to their employees.

Often a formal course cannot be added to the curriculum due to time constraints but a single lecture could be included in other courses such as fluid mechanics, reaction engineering and transfer processes, that would show how the concepts being taught can be applied to mixer design and operation. These lectures could be made available as webinars aimed at undergraduates and more broadly to engineers in industry seeking continuing education.

Even though a formal course may not be feasible, given the constraints of the curriculum, but mixing experiments could be incorporated into junior and senior laboratories demonstrating some of the principles governing mixing processes. This should prepare graduating students to enter the workforce with some understanding of mixing operations.

In this paper the equipment required to perform a series of experiments, developed at the University of Arkansas[2], will be described. Also some of the experiments will be covered with the lessons that the experiment will convey.

Equipment

The equipment is shown in figures 1 and 2.

Figure 1 shows the vessel which is glass, 210 mm in diameter with 250 mm straight side and a flat base. There is a removable steel ring to which four vertical baffles are attached. The width of the baffles is 1/12 of the vessel diameter which is standard in industry. This allows experiments to be carried out in baffled and unbaffled configurations.

The drive has a 1 kW motor with a maximum operating speed of 1800 RPM and is supported from a steel frame. The speed is controlled by a variable frequency drive (VFD) which has torque and rotational speed indicators.

A variety of impellers are included in the kit and shown in figure 2. These include a narrow-blade hydrofoil (figure 2a), a wide-blade hydrofoil (figure 2b), a pitched blade turbine (figure 2c) and a Rushton turbine (figure 2d). The diameter of the impellers will be 1/3 and 1/2 of the vessel diameter.

The impellers have different power and flow characteristics and this will be one of their properties that will be studied in the experiments.

Experiments

Power Measurements

The power drawn by an impeller and the power input per unit mass are often used as a measure of "mixing intensity". The power input by an impeller is calculated from:

$$P = Po\rho N^3 D^5 \qquad \text{... Eqn (1)}$$

P is the power measured in Watts, ρ is the liquid density measured in kilograms per cubic meter, N is the impellers rotational speed measured in revolutions per second and D is the diameter of the impeller measured in meters.

Po is the impeller's power number and it is essentially and drag coefficient, dependent on the geometry and number of the blades.

The motor speed controller has a built in torquemeter which measures the torque on the agitator shaft as the impeller rotates. The relationship between torque and power is:

$P = 2\pi N\Lambda$ … Eqn (2)

Λ is the torque measured in Newton meters.

From equations (1) and (2), the impeller power number is related to the torque by:

$$Po = \frac{2\pi\Lambda}{\rho N^2 D^5}$$ … Eqn (3)

The measurements should be made over a range of liquid viscosities ensuring that they cover the laminar, transitional and turbulent regimes.

The power number is plotted against the impeller Reynolds number and the results will show that, in baffled vessels:

- In the turbulent regime, the power number is constant.
- In the laminar regime, the power number is inversely proportional to Reynolds number.
- The relationship between power and Reynolds numbers in the transitional is dependent on the impeller type.

The key lesson of these experiments is that impellers operating in agitated vessels are pumps (essentially machines that move liquids) and their performance characteristics can be assessed using this comparison.

The power number is analogous to the term:

$$\frac{fL}{d}$$ …Eqn (4)

used for pressure drop calculations and pump sizing in pipe flow. Here f is the friction factor, L is the pipe length and d is the pipe diameter.

Blend Times

In these experiments the time taken for a tracer to be dispersed and blended into a miscible liquid is measured. The measurements can be made using an acid-base color change or conductivity probe. The color change is subjective, depending on the observers' determination of the end point, while the conductivity technique is objective. A typical trace of conductivity versus time is show on figure 3.

Initially the experiments will be carried out in water (or acid and base). If conductivity probes are available the tracer could be a solution of sodium chloride with, approximately, the same viscosity as the liquid in the vessel.

The aim of the experiments will be to determine the relationship between the measured blend times and the impellers' operating speed, type and diameter. The measurements should be made for each impeller for at least three operating speeds.

The data are typically presented by plotting the dimensionless blend time, which is the product of the measured blend time, θ, and the impeller operating speed, plotted versus Reynolds number.

The value of the dimensionless blend time is dependent on the impeller type and geometry. The impellers' power numbers and impeller to vessel diameter ratio account for the effect of these properties on the dimensionless blend time.

The blend time can also be plotted versus the power input per unit mass to show which impeller is the most energy efficient, i.e. achieves a desired blend time for the lowest power input. This result can then be related back to the understanding of pump efficiency that has been shown in the power measurements.

If time allows, the same measurements can be made in viscous liquids to show the effect of viscosity on the blend time in transitional and laminar operation and finally the effect of adding a viscous tracer to a low viscosity liquid could be examined.

The expected relationships between the blend time and the impeller speed, geometry and operating regime are explained in the Handbook of Industrial Mixing[3] and the students could be directed to check their results with this reference.

Solids Suspension and Dissolving Time

In this set of experiments the impeller speed required to "just suspend" particles in a slurry will be measured. The common definition of the just suspension speed is the speed at which no particles are stationary on the vessel base for longer than 1 – 2 seconds. It has been shown that this is the optimum speed to operate and agitator when the particles are dissolving.

The vessel will be filled with water and glass Ballotini beads of known diameter will be added forming a slurry. The agitator speed will be adjusted until the just suspension speed is attained. This is assessed visually by the students. Once this measurement is completed, extra beads should be added to change the concentration. Also, the experiments can be repeated with another size of beads. If time allows, the impeller type and diameter can be changed to investigate their effects on the just suspension speed.

Then sodium chloride crystals can be added to the vessel and the time to dissolve measured. The agitator speed should be set at just suspension speed which can be estimated from analysis of the Ballotini data. The dissolving time can be estimated by observing the disappearance of the particles or from measuring the increase in conductivity as the salt dissolves. Then this experiment should be repeated at lower and higher speeds to investigate the effect on dissolving time.

The purpose of this set of experiments is to show that when the impeller operates above the just suspension speed there is little change in the dissolving time. The reason for this is that the resistance to mass transfer is diffusions through the liquid film at the surface of the particles. Below this speed, when there are particles settled on the vessel base, the resistance to mass transfer is diffusion through the settled bed.

Benefits

These experiments expose students to fluid mixing, in most cases for the first time. They are focused on understanding mixing processes that that they will experience in practice.

The students are also encouraged to compare their results with those reported in the literature and, as they search, they will realize that there are often several correlations that have been developed to describe the processes. This will demonstrate the need to develop some critical skills to determine which accurately reflect reality.

Finally mixing is subject that draws on other subjects, such as fluid mechanics, heat and mass transfer and reaction engineering, and can provide a synthesis of subjects taught in the chemical engineering curriculum.

Pathforward

The North American Mixing Forum is dedicated to promoting the study of mixing as an engineering discipline. NAMF is proposing to lend the necessary equipment to chemical engineering departments who commit to running the experiments in junior and senior labs

Acknowledgements

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References

1. Smith, J. M., "Industrial needs for mixing research", Trans. IChemE, 68, pp. 3 – 6, 1990.
2. Penney, W. R., "Table-top fluid mixing experiments for the laboratory or classroom", In *MIXING XXII*, Victoria, BC, Canada, June 2010.
3. Grenville, R. K. & A.W. Nienow, "Mixing of Miscible Fluids", In *NAMF Handbook of Industrial Mixing*, (E. L. Paul, V. A. Atiemo-Obeng and S. A. Kresta eds.), Wiley, NY, 2004.

Figure 1: Vessel, baffles, motor and speed controller

Figure 2a: Narrow blade hydrofoil

Figure 2b: Wide blade hydrofoil

Figure 2c: Pitched blade turbine

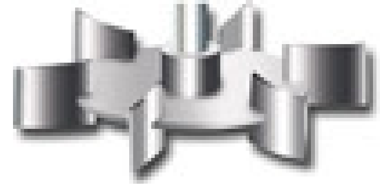

Figure 2d: Rushton turbine

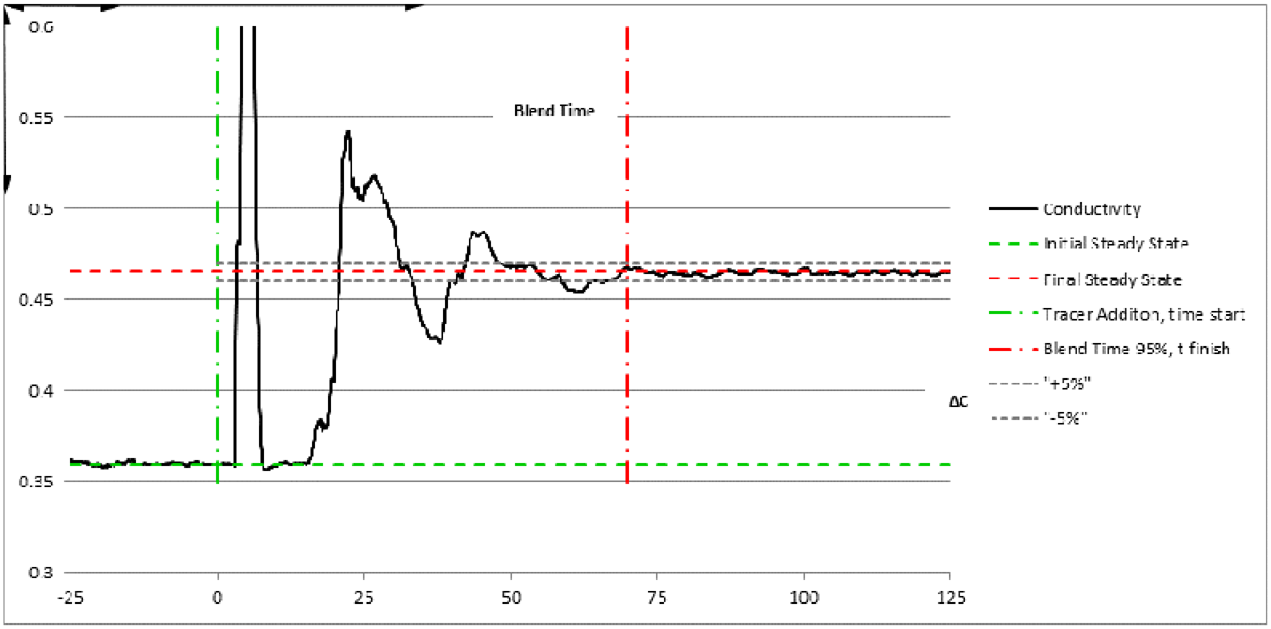

Figure 3: Conductivity versus time for blend time measurement