

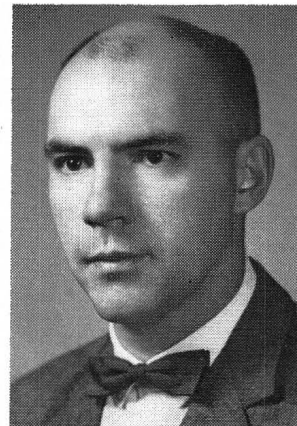
Providing Meaningful Laboratory Experience for Undergraduate Students in Transport Phenomena

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Stated rather broadly, the objective of an undergraduate course in transport phenomena is to help students develop an understanding of, and the ability to apply, those concepts and principles which are involved in the transport of mass, momentum, and energy. Included among the concepts are the notions of velocity, stress, rate of strain, viscosity, thermal flux, temperature gradient, thermal conductivity, heat generation rate, mass flux, concentration gradient, diffusivity, and others. The principles are six in number: conservation of mass, momentum, and energy; Fick's law of diffusion; Newton's law of viscosity, and Fourier's law of thermal conduction. Since the ideas of transport phenomena are basic to many of the methods employed by chemical engineers, it is appropriate that we should exploit whatever techniques are available to accomplish our objective.

Probably without exception, the stimulus on which primary reliance is placed is the professor's lecture. In most courses, reading assignments are made from one of the standard textbooks, and homework problems are assigned to help the student gain facility in applying the principles. A conscientious professor may employ some of the film strips or short movies which are now available, and he may even present a demonstration or two. All of these are certainly valid instructional techniques, but they can be richly complemented by experience gained in a well-designed laboratory. The purpose of this paper is to describe our attempt to provide such experience for students at the junior level.



We have devised a set of experiments, each of which has to satisfy the following criteria before being accepted for inclusion in the laboratory.

1. It has to accomplish certain clearly stated objectives.

2. It has to be capable of producing experimental data which are in reasonable, say ± 10 percent, agreement with theoretical predictions.

3. It has to be relatively free of extraneous complications.

4. The equipment has to be relatively inexpensive to obtain and easy to maintain.

The methods that we have used to meet these criteria can be presented most easily by describing the first experiment.

This experiment takes two weeks to complete, although much of the first laboratory period is devoted to administrative and operational details. It concerns laminar flow in circular tubes, and its objectives are stated as follows:

1. To enable the student to visualize the velocity field for flow through a circular tube.

2. To generate some confidence in the correctness of the theory of Newtonian fluid mechanics in general and in the Hagen-Poiseuille equation in particular.

3. To develop an appreciation for the two externally applied forces to which fluids are normally subjected in tubes. These are a longitudinal pressure gradient and the force of gravity.

4. To illustrate an important limitation which must be applied to any theoretical analysis based on laminar flow. This is the transition from laminar to turbulent flow which occurs when the velocity exceeds a critical value.

5. To illustrate the use of a manometer to measure pressure in a fluid.

The principal piece of equipment used in this experiment is a constant head tank. It will be

described in more detail later, but now it will suffice to mention that the outlet fitting can accept either a piece of 14 mm glass tubing, which projects up into the tank, or any other piece of equipment which terminates in $\frac{1}{2}$ in.-OD tubing. In the second part of this experiment we attach a piece of 3/16 in.-OD aluminum tubing to the outlet fitting. The connection is made through a reducer and a short piece of plastic tubing which permits the angle of inclination of the 3/16 in. tubing to be changed during the experiment. The tube is fitted with pressure taps near the inlet and outlet ends. Manometer tubes which are open to the atmosphere are used to measure the pressure.

The experiment is performed in two parts. In the first part, which is the well-known Reynolds experiment, the students observe flow through a vertical section of 14 mm glass tubing. A piece of capillary tubing is used to inject a dye filament into the stream near the center of the larger tube. The flow rate can be adjusted with a valve located at the discharge end of the tube. It is possible for the students to observe that the flow is laminar at low velocities and becomes turbulent at higher velocities. The velocities are low enough that they can be measured with a graduated cylinder and a stopwatch. When a large blob of dye is injected into the stream, the students can see it deform into a well-defined parabola as it progresses down the tube. Again the velocity of the leading edge of the colored fluid is low enough that it can be measured accurately with a stopwatch and a meter stick. Hence, the student readily confirms that the centerline velocity is twice the average velocity. It is also worth mentioning that this is an esthetically pleasing experiment; the students enjoy the experiment, and it gets the laboratory off to a good start.

In the second part of the experiment, the glass tube is replaced by the 3/16 in. tube, and the manometer levels are measured at various angles of inclination and flow rates. A removable valve at the discharge end of the tube permits the flow rate and the angle of inclination to be varied independently. In analyzing their data, the students are asked to make two graphs: volumetric flow rate with the valve removed versus difference in elevation between the liquid level in the reservoir and the discharge end of the tube, and difference in manometer levels versus flow rate. If the flow is laminar and one can neglect all frictional losses except those in the tube, the

first graph should be a straight line with a slope of $\pi R^4 \rho g / 8 \mu L$. Actually, the resistance of the inlet fitting is not completely negligible, and the measured slope is slightly smaller than the theoretical value. Since he can see from the manometer reading that the pressure at the inlet end of the tube falls as the flow rate increases, the student readily arrives at the correct explanation for the discrepancy. The second graph is quite free from spurious effects, and the experimental data agree well with the theoretical curve. It should be noted that the difference in manometer levels is equal to the pressure drop due to viscous losses; the gravitational force exerted on the fluid in the tube is balanced by the extra gravitational force exerted on the fluid in the manometer line leading to the upper pressure tap. Providing a proper explanation for this phenomenon forces the student to think clearly about the various forces which act on a fluid in a tube.

This experiment was designed so that the flow would be laminar over most of the accessible range of velocities. At the higher flow rates, the critical Reynolds number is exceeded, which can be seen clearly by the student because the flow tends to become unsteady in the transition region. His graphs also tend to deviate from the theoretical curves at the transition point. He is asked to calculate the Reynolds number at the transition point, and values in the range from 2100 to 2500 are usually obtained. Furthermore, his experience in the first part of the experiment prepares him to accept the notion of an eddy diffusivity and an eddy viscosity, both of which greatly exceed the corresponding molecular values. Hence, he can predict qualitatively how his experimental data in the turbulent region should deviate from the theoretical curves for laminar flow.

We feel that this simple experiment illustrates many ideas that are fundamental to hydrodynamics. Since the same ideas are presented in the classroom, one can ask, "Why go to the trouble of setting up a laboratory in which experiments such as this can be performed?" The answer to this question, in our opinion, is that concepts gained through laboratory experience tend to be more vivid and lasting than those gained in the classroom. Furthermore, a higher level of problem solving is involved in analyzing experimental data than in solving most textbook problems. The student has to devise the problem that pertains to his particular experiment before he can solve it. He has to recognize what is important and what can be neglected. And finally, he profits by

his own mistakes if he is persistent enough to bring the experimental and theoretical results into agreement. We have found that the last point is very important, but it can only be realized if the experiment is designed in such a way that accurate data can be obtained.

If a laboratory such as this is to complement the lecture course, timing is important and all of the students must be doing the same experiment at the same time. Adequate access to the equipment can be achieved only if the students work in groups of two or three. This means that as many as ten complete sets of equipment may be required at a large university. We have tried to make this possible by designing small pieces of apparatus, individual parts of which can serve many purposes.

For example, the constant head tank mentioned earlier was made from a three liter stainless steel beaker. Two holes were cut in the bottom of the beaker. An overflow pipe was soldered into one of the holes, and a one-half inch bulkhead fitting of the Swagelok type was fastened into the other hole. An O-ring groove, cut into the inside surface of the bulkhead fitting, permits a water tight seal to be maintained around the piece of 14- mm glass tubing which passes through the fitting. Of course, any other piece of equipment terminating in one-half tubing can also be attached to the fitting. This feature enables us to use the constant head tank in five distinct experiments.

The second hydrodynamics experiment is a tank-emptying experiment for which it is only necessary to turn off the inlet flow line. In the third experiment, the behavior of a siphon is studied, and the constant head tank is used again as a reservoir. We also do a heat transfer experiment in which transient heating and cooling of the contents of the tank are studied. Although the details have not been completely worked out, we also plan to devise a transient state mass transfer experiment.

In the case of the heating experiment, the heater is a small finned-tube heat exchanger, which passes through the Swagelok fitting in the bottom of the tank, and is sealed by the O-ring. The lower end of the heater fastens directly onto a small electrically heated boiler that can provide over a kilowatt of power. The boiler also serves several purposes. In addition to providing steam for the tank heating experiment, it provides steam for a thermal conductivity cell in which

heat transfer through composite slabs is studied. It also provides steam for the annular region of a small concentric tube heat exchanger.

By reducing the size of our equipment, keeping it relatively simple, and making the more expensive pieces perform multiple functions, we have been able to obtain the necessary equipment with a rather modest capital outlay. It is also worth noting that, since the equipment is small in size, finding adequate storage space is not a problem.

The experiments are performed in one bay of a large laboratory. This bay has been fitted with a number of "distillation racks." Electrical power, water, air, and drains are provided at each of the racks. The equipment can be mounted easily on a rack and left there for several days if necessary. This permits the students to come back and repeat part of an experiment or obtain additional data. Hence, they are not as pressed for time as they might otherwise be, and they can be held responsible for the accuracy of their observations.

In this brief paper an attempt has been made to describe the approach that we have used to provide meaningful laboratory experience for an undergraduate class in transport phenomena. A considerable amount of effort has already gone into this project, and more will be required before a really satisfactory result is achieved. Hopefully, others can benefit from our experience as we have benefitted from the experience of those who preceded us.

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