FLUID FLOW EXPERIMENT FOR UNDERGRADUATE LABORATORY

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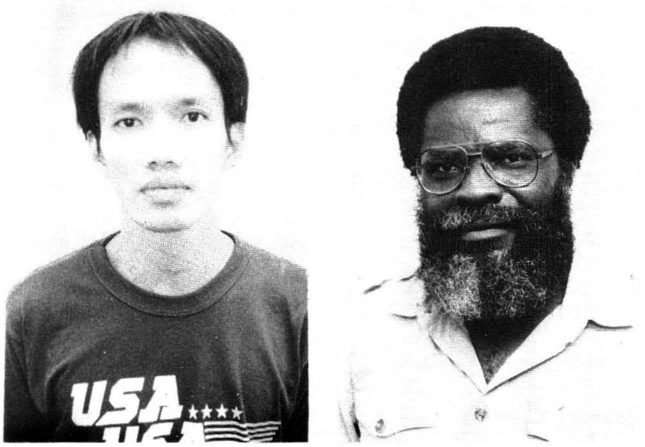
OUR UNDERGRADUATE FLUID mechanics laboratory consists of three experiments: mixing, drag measurements, and fluid flow and pressure drop measurements. The latter is the subject of this paper. Like much undergraduate laboratory equipment, our fluid flow apparatus was at least twenty years old. It relied on a once-through gravity flow of local tap water through iron and copper pipes which was not only wasteful, because water was discharged directly into the sewage system, but also introduced difficulties in the winter due to dissolved gases in the water. Instrumentation in the experiment included a venturi, an orifice meter, a rotameter, a pitot-static tube and two pipe lengths of copper and iron for measurements of friction factor. Data for pressure drop were obtained using mercury and inverted air-water U-tube manometers.



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Aside from being unnecessarily complicated, with more than twenty valves (many of which had to be manipulated simultaneously), the results obtained with this old rig were often unreliable due to fouling and corrosion. Also, since the cost for local water had more than tripled during the past four years, it was apparent that a straightforward solution would be to replace the equipment. Prior to our decision to build a rig ourselves, a careful evaluation of commercially available laboratory teaching equipment was made. Aside from the cost consideration of these units, at least two separate rigs would be needed to accomplish some of our objectives. Since acquisition of two or more units would also involve laboratory space problems, purchasing the equipment became a less attractive alternative.

Several important criteria were established for the new design. First, no more than a hundred gallons of water should be used during one semester, a requirement that dictated the use of a closed flow loop. (This value is less than one-half of the daily requirement for the old experiment.) Second, piping material for the test sections must be of clear plastic and pressure lines must be of tygon plastic tubing, to enable visual observation of the flow pattern and purging of the system. (Pressure lines in the old rig were of copper tubing.) Third, the construction must be flexible enough so that additional flow measuring devices and flow visualization techniques can be incorporated with minimum effort and delay. (This was one of the underlying reasons for rejecting commercial units.) Fourth, data for friction factor must cover the laminar, transitional and turbulent flow regimes.

EQUIPMENT DISCRIPTION

The description of the experimental facility, shown schematically in Fig. 1, is sufficiently detailed to permit immediate incorporation into existing undergraduate laboratory programs. It consists of an Oberdorfer 13 HDL gear pump, driven by a 1.5 hp DC variable speed motor, which delivers water from a Nalgene 55 gallon polypropylene storage tank through a back-flow preventing valve and into a Sears glass-lined water tank (0.5m (OD) and 0.9m high). The latter, which is used as a surge tank, was salvaged from scrapped equipment. The maximum pressure in the surge tank is limited by a cut-off switch set at 30 psig and connected to the motor controller power supply. From the surge tank the water flows through three transparent plastic pipes of internal diameter 50.8, 25.4 and 12.7 mm and then back to the supply tank.

The 50.80 mm diameter pipe loop contains a 12.7 mm diameter square-edged orifice (*i.e.* diameter ratio, $\beta = 0.25$) and also valved into this loop is an Ametek 6HCFB-61J laboratory rotameter (range: 1-24 gpm). Upstream and downstream tap locations for the orifice are one and one-half pipe diameter respectively. Average pressure at each location is determined from the readings of three equally-spaced circumferential taps using manifolds, the outlet from the manifolds being connected to a U-tube mercury manometer. The flow rate in the line is varied using the motor speed controller. The reason for use of the latter rather than the control valve is discussed later.

Flow through the three line segments of the 12.7 mm diameter loop, into which is also valved the smaller range rotameter (4HCFB-40J, range: 0.1-5 gpm), is controlled with a Whitey stainless steel valve having a teflon seat and stem tip. Average wall static pressures in two of these segments are measured by flush-mounted pressure taps, spaced 0.61 m apart. In each case, the upstream and downstream taps respectively are 98 and 73 pipe diameters after and before an elbow. At each location, the three circumferentially placed taps, made from 1.6 mm (O.D.) brass telescoping tubing, are connected to a manifold. The pressure

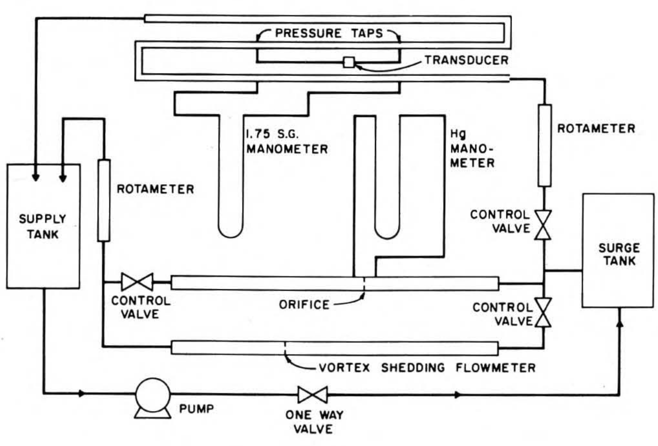

FIGURE 1

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drop acrosss the two 0.61 m lengths, to be used for computation of friction factor, is recorded by a U-tube manometer filled with a 1.75 specific gravity fluid and by a Validyne DM 56 differential pressure transducer assembly, the latter being designed to give direct digital readings in inches of water.

It is of some interest to note that after preliminary tests in our laboratory, the original Validyne factory sets were returned to the manufacturer for modifications. These included changing the transducer diaphragm, as well as recalibration of the unit, to give a full-scale pressure range of ± 101.6 cm of water. Also, the internal filter valve in the digital indicator was changed to 0.1 Hz.

There are several additional comments. First, connections at critical points (before and after each rotameter, between the surge tank and the piping network) are made with reinforced automotive radiator hoses, as this facilitates modifications to the equipment. Next, two purge valves are provided at the inlets to each manometer. Also, since the principle of operation of an orifice and a venturi is essentially the same, the latter is not included in the new experiment.

Another general comment deals with the operation of the equipment. Since each laboratory group consists of three students, the recommended procedure is to consider one flow loop at a time. When working with the 12.7 mm diameter loop, the control valve in one of the remaining loops must remain open for transport of excess water back to the storage tank, minimizing pressure build-up in the equipment.

As previously mentioned, flow through the orifice is controlled with the motor speed controller rather than with the control valve (Fig. 1). This decision was made after the equipment was started several times with the control valve completely closed. Apparently, some students have had little exposure to flow control with valves and are confused when it comes to deciding which direction to turn a valve for open or close. The consequences were exactly as might be expected: damage to pressure lines and fittings, unwanted shower baths, loss of mercury since no traps were provided, and delay in completion of the experiments because of time needed for repairs. For the 25.4 mm and 50.8 mm diameter loops, the control valves should be used primarily for isolation of a loop while variation of the flow rate should be accomplished with the motor speed controller. It should be noted that there is at

TABLE 1
Orifice Discharge Coefficient

*Re x 10^{-5}:	0.17	0.36	0.52	0.59	0.64	0.81	0.92	1.07	1.13	1.22
C_o :	0.64	0.65	0.64	0.64	0.62	0.63	0.63	0.64	0.62	0.63

*Based on orifice diameter

least one advantage to using the speed controller for control; the scale (0 to 100) facilitates repeatability.

EXPERIMENTAL PROCEDURES

When the flow is initially started, bubbles in the piping system are clearly visible and purging is easily accomplished. Calibration of the rotameters and the orifice, as well as pressure drop measurements, are fairly straightforward and involve the collection and weighing of water over an elapsed time. For low flow rates (usually 0 to 60 mm reading on the smaller range rotameter), the water collected is weighed on a Mettler 2000 electronic balance capable of reading as low as 0.01 gm, while a Toledo scale is used for higher flow rates. Since the pressure transducer must be calibrated and no external source is provided for that purpose, it is accomplished by using the actual pressure drop in the pipe as measured by the 1.75 specific gravity U-tube manometer for the turbulent flow regime. The fact that the span (or gain) adjust control on the digital transducer indicator can be set arbitrarily permits use of different gain factors for different laboratory groups. Since it is unusually difficult to obtain accurate pressure drop readings with the U-tube for low Reynolds numbers, construction of the complete f vs. Re plot by any particular group depends on the ability to establish the gain factor corresponding to the setting on the control.

There is an interesting comment on the use of different gain factors. Here at Clarkson, each laboratory group is required to submit a preliminary report prior to performing an experiment and a final report upon completion. Since these reports are produced using our computer facilities, possible swapping of reports and data was of some concern. Altering the gain of the display was intended to reveal such a practice. Surprisingly, although thirty-seven groups have used this equipment, the fact that the gain was deliberately changed from group to group has so far been undetected by the students; at least no group drew our attention to the differences in the gain of the display.

RESULTS

In addition to the plots of mass flow rate versus rotameter reading and the square root of the pressure drop for the orifice, each group is required to calculate the orifice discharge coefficient (C_o) for each Reynolds number (Re). Typical results obtained by the students are presented in Table 1 from which it can be readily established that the average value could be stated as 0.634 ± 0.010 for Re $\geq$ 17,000 and $\beta = 0.25$, in close agreement with the available literature [1] for an orifice of comparable design.

For pressure drop, expressed in terms of the Fanning friction factor, two plots are required: the familiar log-log plot of f vs. Re and a linear plot of

$$1/\sqrt{f} \text{ vs. } \log_{10}\mathrm{Re}\sqrt{f}.$$

The first plot, typical results of which are presented in Fig. 2, illustrates the transition from laminar to turbulent flow, while the second (not shown here due to space limitations), an alternative representation of the same experimental data, is intended to familiarize the student with the more practical concept of the universal resistance formula for smooth tubes.

It can be seen in Fig. 2 that the students' results for turbulent friction factor are closely approximated by the well-known Blasius equation. Although the laminar results are not as accurate as one would wish, due primarily to the resolution (0.01 inch of water) of the digital transducer indicator, they nonetheless confirm that transition from laminar to turbulent flow occurs in the range of Reynolds number between 2,000 and 3,000. For laboratory instruction, the resolution of the digital indicator is quite satisfactory.

ADDITIONAL FEATURES

Up to this point, we have dealt with the general features of the equipment, experimental procedures, and some of the results. In this section, we will briefly describe two features that have been included in the experiment. The first, a reflection of the latest technology in flow measurement, involves installation

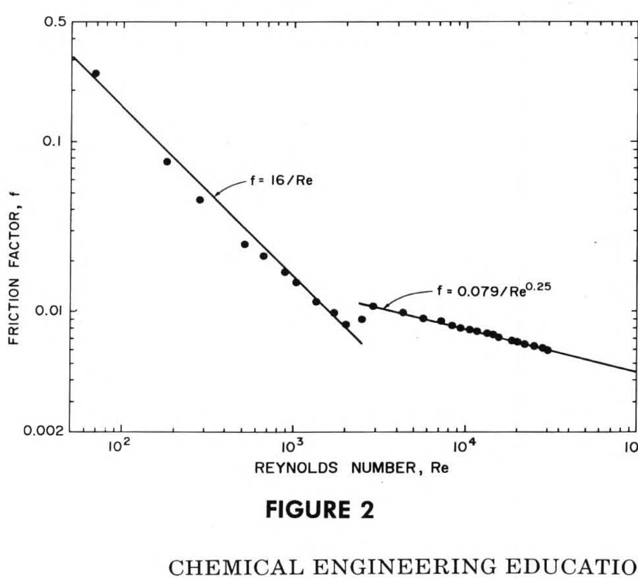

FIGURE 2

of an Eastech 2350 vortex shedding flowmeter. This unit is valved into a separate, clear plastic, pipe loop as shown in Fig. 1. Internal diameter of the pipe is 25.4 mm, this loop's control valve being also of stainless steel. With the ancillary signal processor, digital display of the flow rate (in gpm) is obtained. Since the fluid flowing past this device is fed to the rotameter (Fig. 1), this meter's readings can be compared with those obtained by weighing. Also, the straight entrance length required before the meter and the fact that the minimum measurable flow rate is much higher with a 50.8 mm than with a 25.4 mm diameter pipe, necessitated inclusion of a separate pipe loop.

The choice of a vortex shedding flowmeter over other sophisticated and nearly fool-proof systems, was made because of its educational value. In the first place, its principle of operation (that of vortex shedding when real fluids flow past submerged bluff objects) is a natural phenomenon and is usually covered in undergraduate fluid mechanics course. Also, with clear plastic pipe, the vortex shedding frequency can be observed using a strobe-light assembly.

Another feature that has been incorporated involves installation of a series of 1.6 mm diameter flush-mounted pressure taps upstream and downstream of the orifice. This is intended to highlight the dependence of orifice discharge coefficient on pressure tap locations, as well as the trends in pressure distribution in the vicinity of surface mounted protrusions.

CONCLUDING REMARKS

The design of a versatile fluid flow experiment for undergraduate instruction has been presented. The flexibility in design and construction facilitates addition of some of the latest technology in flow measurement. The equipment is inexpensive when compared to the cost of commercial units with limited features. In addition to the supplies, about a week of a technician's time is required for construction of the unit.

As to the laboratory teaching procedure, it may be noted that each group of three is required to carry out this experiment, and drag measurement or mixing, during a two-week period. Even with the additional features noted above, seven hours of laboratory time are allowed for this experiment, as is the case for the other fluid mechanics experiment. Groups that do not complete an experiment during the scheduled period are required to do so on their own time. In general, each group is required to give an oral progress report after completion of the first of two laboratory periods. Plots of all data obtained during the first laboratory period, along with typical calculations, must be presented to the instructor just before the oral presentation.

REFERENCE

1. *Chemical Engineers' Handbook*, R. H. Perry, et al. (eds.), 5th ed., McGraw-Hill, N.Y. 1973. □

ChE book reviews

THE CHEMISTRY TUTOR: BALANCING EQUATIONS AND STOICHIOMETRY

By Frank P. Rinehart
Wiley Educational Software, Wiley & Sons, Inc., $25.00 (1984)

Reviewed by
Pradeep B. Deshpande and Walden L. S. Laukhuf
University of Louisville

The Chemistry Tutor consists of programs designed for use with the APPLE II+ or IIe computer with a disc drive and DOS 3.3. The programs deal with balancing equations, stoichiometry, and limiting reagents.

The first set of programs is designed to teach the user how to balance chemical equations. The exercises ask the user to select the coefficients in the equation, and the program checks whether the equation is balanced. If the equation is balanced the user moves on to the next exercise. If not, another set of coefficients may be entered and checked for correctness. The user has the option to ask for help through a tutorial. The tutorial asks how many atoms of each element are present on each side of the equation. Sooner or later the reader discovers what element is not in balance.

The second segment deals with stoichiometry. The exercises enable the user to decide how much of a reactant or product is consumed or formed given the mass of any other reactant and product. The final set of programs is concerned with limiting reagents. The objective, in this instance, is to decide how much of any product could form given the specified amounts of two reactants, when one of them is a limiting reagent.

The programs are well written and are user friendly. Unfortunately, the exercises are too elementary for college level students. The usefulness of the programs would be enhanced if the author could be persuaded to include the analysis of redox reactions by change in oxidation state or ion-electron technique.

The reviewer was assisted by Prof. Emeritus P. M. Christopher in the review. His assistance and comments are gratefully acknowledged. □