A New Multipurpose Fluid-flow Experimental Module

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In 1996, we designed and implemented a mobile fluid-flow apparatus that has found immediate and wide application at various levels of our undergraduate and graduate programs. The reasons for the success of this module are its ease of use and breadth of application.

The fluid-flow experimental module is built into a standard mobile cart that can be wheeled conveniently to different classroom and laboratory sites, both within our Engineering Center and to adjacent buildings on the Boulder Campus of the University of Colorado. The apparatus is controlled by computer using the National Instruments' LabVIEW software running on a notebook PC. The interface is via the printer port of the PC, thus avoiding specialized interface cards internal to the computer; consequently, different computers can be used conveniently.

The structure of the fluid-flow module is simple: it is a single water circulation loop with flow driven by a small centrifugal pump. Circulation rate is manipulated via an electronic control valve and measured with an electronic turbine meter. Water flows into the top of a 1-meter-high acrylic standpipe and exits the standpipe through a 9-meter-long helical coil of plastic tubing. The plastic tubing ejects the water into a sump tub which is connected to the suction of the pump. The level in the standpipe is measured by an electronic differential pressure transmitter. The various instruments are interfaced to a National Instruments' DaqPad unit which provides for the printer-port PC interface.

The intended use of the fluid-flow module was to bring "O.D.E.'s in action" to our common sophomore-level course, Introduction to Linear Algebra and Differential Equations. In the Fall 1996 semester, nearly 300 students, organized in groups of four, ran experiments using the module and compared transient level response to that predicted by a coupled set of continuity and mechanical energy balance equations. The unit was designed to have complex eigenvalues at low operating levels and real eigenvalues at higher levels; consequently, it displays both underdamped and overdamped behavior, depending on the operating conditions. Student groups operated the LabVIEW interface with minimal difficulties and minimal instruction.

Additionally, the module has found use in the following settings:

⇒ demonstration only in a freshman-level technological literacy course for liberal arts students
⇒ sophomore-level fluid mechanics course: fundamental modeling & comparison with data
⇒ junior-level applied data analysis course for ChE students: regression analysis
⇒ junior-level ChE laboratory course: analysis of fluid friction
⇒ graduate-level numerical methods/modeling course: eigensystem analysis
⇒ senior-level process control course: implementation of feedback control including cascade

Because of the unexpected demand for the module, we are considering several additional units of identical design. The total cost of one module, including computer interface but excluding computer, is less than $5,000.

The fluid-flow experimental module will be housed (or garaged) in our College's Integrated Teaching Laboratory in 1997.

Design Principles for Experimental Modules

Although the benefits associated with the use of experiments in instruction, whether through demonstration by instructor or hands-on use by students, are widely touted and generally accepted, the problems that limit the impact of these activities are not so frequently cited. The following characteristics are seen as important for experimental modules that are to be used in instruction:

- portable & self-contained
- quick start-up
- ease of operation
- simplicity and visual impact
- more than meets the eye

In order to gain wide and frequent usage, an experimental module must not require various pieces of equipment to be assembled each time the module is to be used. The unit must be self-contained and able to be moved conveniently to the site of the demonstration or use. At most, electrical service should be required. The module cannot require an extensive start-up procedure or its users, both instructors and students, will lose patience and interest. Operation of the unit must be straight forward and intuitive. If extensive training is required, use will be limited.

An experimental module will be most effective if it is designed to provide a visual impact. This impact will be aided by simplicity in design and hampered by complexity. At the same time, modules that demonstrate phenomena in a qualitative fashion without real measurements will lack the follow through required for thorough learning. It is ideal if an experimental module is relatively simple on the surface and simple in design, yet possesses characteristics that show complexity below the surface.

Of course, beyond these design principles come essential matters of cost and feasibility.

Motivation for the Fluid-flow Module

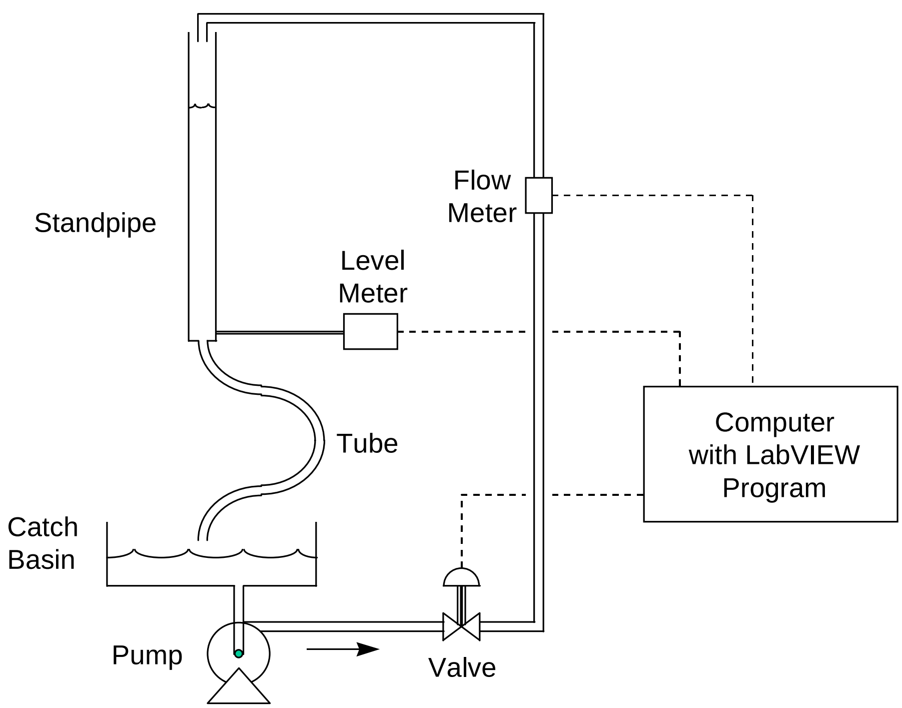
In his established text, *Process Modeling, Simulation and Control for Chemical Engineers*, Bill Luyben describes a reservoir and exit pipe system shown in the diagram below.

By writing dynamic differential equations for the volume balance in the reservoir and for the mechanical energy balance in the pipe, he shows that, for a given set of design and operating parameters, this system behaves in an underdamped manner with natural oscillations. It is easy to show that for other parameter sets, it does not, but rather behaves with overdamped characteristics. This simple system, with intriguing fluid dynamics, inspired the design of a small-scale fluid-flow module.

We hear unending complaints from students that they have difficulty grasping abstract concepts without some reference to reality. This is particulary true in the mathematics taught to engineering students. Since differential equations are used so widely in modeling real systems, the fact that they are taught in an abstract manner is of concern. Having the concept of the fluid-flow module in mind, we proposed that this module could best be used at the point where students were learning differential equations, rather than later on in fluids, dynamics & control, or general laboratory courses. The idea was simple: attempt to bring some life to differential equations with a real system.

Description of the Fluid-flow Module

The module is shown in the following diagram and is build on a mobile cart.



It consists of a water circulation system with a standpipe, exit tube, catch basin and centrifugal pump. The general dimensions are as follows:

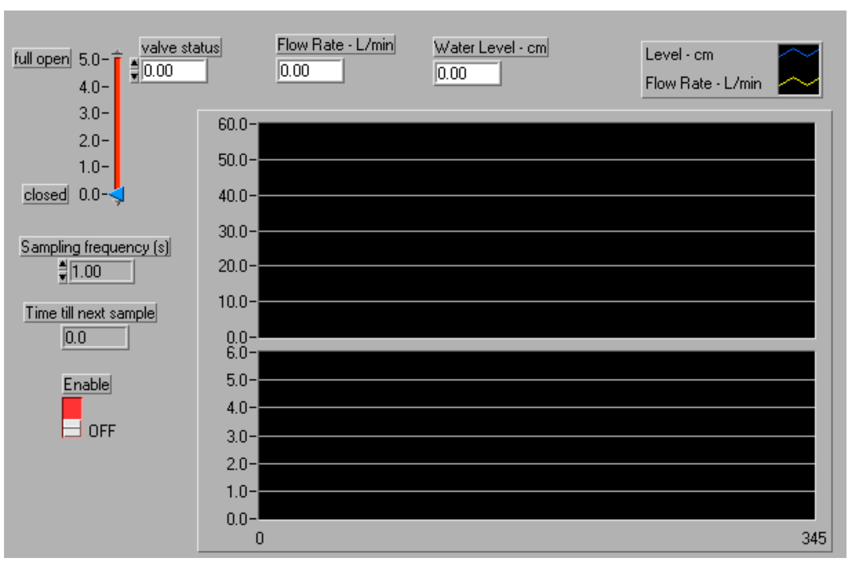
standpipe: 1 m tall, 7.5 cm diameter, acrylic
exit tube: 10 m long, 1.25 cm diameter, polypropylene coil

The centrifugal pump was specified with sufficient discharge pressure to overcome the head required to deliver water to the top of the standpipe and do so with a flow rate sufficient to maintain a static level in the standpipe at approximately 60 cm, typically about 6 L/min.

The system was equipped with a turbine flow meter to measure the flow rate delivered to the top of the standpipe and an electronic control valve to adjust this flow rate. Hydrostatic pressure at the base of the standpipe is measured as an indication of liquid level.

The flow meter and hydrostatic pressure (level) meter transmit electronic signals that are acquired by a computer data acquisition interface (National Instruments DaqPad). That interface also produces an electronic signal to command the control valve. The data acquisition interface connects to a computer via its parallel/printer port; consequently, it can be moved easily from one computer to another.

The software used to monitor and control the unit is LabVIEW by National Instruments. A relatively simple "visual instrument" graphical program (called a "vi") was developed to manage the unit. Its front panel is shown below:



The valve can be manipulated by the user by moving the slider in the upper-left-hand corner. Level and flow rate are displayed numerically in the windows along the top, and shown graphically below.

Application of the Fluid-flow Module to a Sophomore Course in Differential Equations

Students in a sophomore-level course in differential equations may not have taken a course in fluid mechanics yet or they may be taking one concurrently; consequently, one cannot depend on such background. The differential equations that describe the fluid-flow module are introduced in the following way.

A differential equation that models the conservation of mass in the standpipe system, based on Eq. 1 above, is

$$\frac{d}{dt}\left(A_p\, h\right) = \rho\, q_{in} - \rho\, q \quad \text{or} \quad \frac{dh}{dt} = \frac{1}{A_p}\left(q_{in} - q\right) \qquad [2]$$

where

ρ : fluid density

A_p : cross-sectional area of standpipe

h : fluid level in standpipe

q_{in} : volumetric flow rate into standpipe

q : volumetric flow rate out of standpipe and in tube

Another differential equation describes the balance of momentum or mechanical energy of the fluid in the tube. This is similar to Newton's 2nd law, $ma = \sum F$ (mass $\times$ acceleration = sum of forces). The equation is

$$\frac{dq}{dt} = \frac{A_t\, g}{L}\left(d + h\right) - f\,\frac{q^2}{2LA_t} \qquad [3]$$

Here,

q : volumetric flow rate in tube

A_t : cross-sectional area of tube

L : length of tube

d : elevation change from bottom of standpipe to exit of tube

f : coefficient of friction

The first term on the right-hand side of Eq. 3 accounts for the driving force for flow due to the column of water in the standpipe. The second term describes the retarding force due to friction in the tube. When these two terms are out of balance, the fluid will either accelerate or decelerate until they are in balance.

The various parameters in the above equations can be classified as follows:

independent variable: t : time

dependent variables: h : water level in standpipe
q : flow rate out of standpipe and in tube

dimensional parameters: A_p : cross-sectional area of standpipe
A_t : cross-sectional area of tube
d : elevation change from bottom of standpipe to exit of tube
L : length of tube

fluid properties: ρ : density

other: g : gravitational acceleration
f : coefficient of friction

The first three of these (t, h, q) are measured by the computer. The dimensional parameters can be measured quite well on the apparatus using calipers and a measuring tape. The fluid used is water, and its density is well known, as is gravitational acceleration. The last parameter, the coefficient of friction (f) is not well known nor can it be predicted well ahead of time, but it can be characterized from an experiment you will run. Finally, when f has been estimated from experiment, the two differential equations can be used to predict how the system should behave during a change from one flow rate (& level) to another. This prediction can be compared to the actual data from this second experiment.

Details regarding the "coefficient of friction" are left out, such as its relationship to a friction factor, Fanning or Moody, loss due to contraction, and the serpentine effect.

A group of three or four students runs two types of experiments within a thirty-minute period. These, along with suggestions for processing the data, are described below:

Experiment 1: Characterizing Fluid Friction

Most of the change in water level, from minimum to maximum, takes place between valve settings of 1.8 and 3.0.

1. Set the valve at 1.8 and wait for the water level to settle out and stop changing. This may take up to 5 minutes. Note down approximate values for the level and flow rate.

2. Increase the valve setting to 2.0 and wait again for the level to stop changing. Note the level and flow rate values again.

3. Continue this procedure in steps of 0.2 to and including a setting of 3.0.

Experiment 2: Step Response

1. Set the valve to some value between 2.0 and 2.5. Note this value. Wait for the level to settle out, and note the flow rate and level values.

2. Increase the valve setting by 0.5. Again, wait for the level to settle out and note the flow rate and level values.

Suggestions for Analyzing the Data from Experiment 1

1. In the data file from the experiment, find sets of values for flow rate and level that represent each steady-state condition. Within each set, compute the average values of flow rate and level.

2. For each steady-state condition, compute a value of the coefficient of friction, f, from your measurements and the basic data, using the formula derived from Eq. 3, with the derivative set equal to zero; that is,

$$f = \frac{2A_t^2 g\left(d + h\right)}{q^2}$$

3. Plot your values of f versus q. See if there is a systematic relationship. If so, model this relationship, perhaps with a straight line. If not, just compute an average value of f.

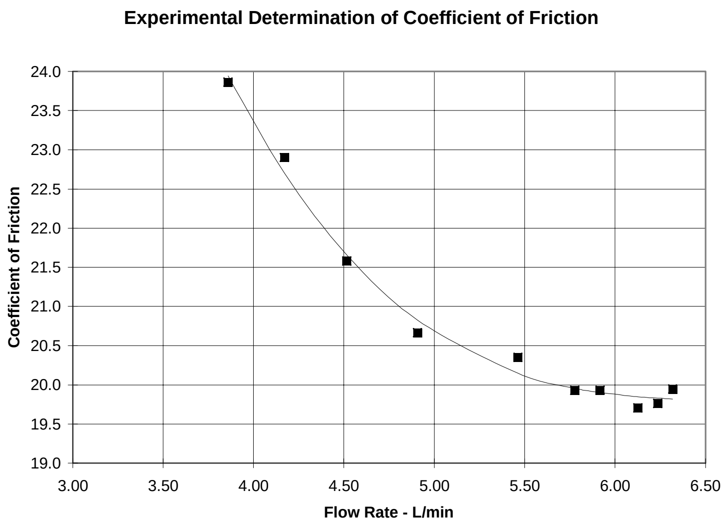
Suggestions for Analyzing the Data from Experiment 2

1. Select data from your file that represent the step test. Create a new set of times by subtracting the time value when the step in flow rate is initiated from all the time values after that. This resets your time scale so time = 0 is at the beginning of the test. Note the initial values of flow rate and level.

2. Given the basic data and characterization of the coefficient of friction from Experiment 1, and the observed initial conditions of flow rate and level, solve the differential equations that model this system. The equations can be solved numerically using an elementary technique, such as Euler’s method, or they can be linearized about the initial conditions and solved analytically for a step-change input.

3. Plot the data and equation solutions for level and flow rate versus time. Compare these curves and make diagnostic comments on any significant differences.

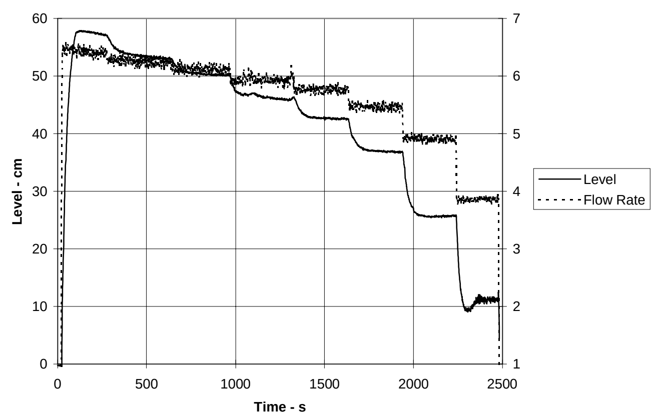
Typical results from the experiments are shown below.



where the curve is a fitted equation,

$$f = 74.4085 - 1.4628\times10^{6} q + 1.3032\times10^{10} q^{2} - 3.8599\times10^{13} q^{3}$$

and



In the Fall 1996 semester, nearly 300 students, in groups of 3 or 4, used the module in conjunction with their differential equations course. Although the results from formal course evaluations are not available at the date of this writing, informal feedback from both students and instructors was positive.

Use of the Fluid-flow Module in Other Courses

During the Fall 1996 semester, the fluid-flow module also found use in the following courses:

Creative Technology -- a freshman-level technological literacy course for non-engineers
Applied Data Analysis -- a junior-level measurements/statistics course
Numerical Methods in Civil Engineering – a senior/graduate-level course

In the Spring 1997 semester, the module is again being used in the differential equations course. It is also planned for use in

Chemical Engineering Laboratory 1 – a junior-level lab course in fluids and heat transfer
Instrumentation & Process Control – a senior-level course for chemical engineers

The module is being used by the author but also by numerous other instructors across our College of Engineering and Applied Science.

Where From Here?

As part of our new Integrated Teaching & Learning Laboratory (ITLL) facility at the University of Colorado, it is proposed to build a number of replicates of the fluid-flow module, perhaps three or four more. These can be used in the ITLL with existing computers and data acquisition interfaces or rolled out to other classrooms or laboratories in our Engineering Center. Subsequent units will cost about $2,500 to build, not including the DaqPad (or equivalent) interface. The latter adds about $1,500 to the cost.

Acknowledgments

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Biographical Information

David E. Clough is Professor of Chemical Engineering at the University of Colorado in Boulder. He joined the faculty there in 1975 and also served as Associate Dean of the College of Engineering and Applied Science from 1986 through 1992. His research and professional interests are centered on process control.