FLUID MECHANICS FACILITIES AND EXPERIMENTS FOR THE MECHANICAL ENGINEERING TECHNOLOGY STUDENT

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Abstract

Three novel experimental fluid mechanics facilities are described in this paper. Typical experiments using these facilities will also be discussed. The facilities are used in teaching the laboratory component for a Mechanical Engineering Technology (MET) fluid mechanics course at Central Washington University (CWU). The facilities and related experiments have been found to be very useful in bridging the gap between theory and hands-on experience. The experimental facilities that will be described in this paper are referred to as: (1) the water flow measurements loop, (2) six inch air flow tunnel, and (3) the Torricelli experiment.

Nomenclature

A_0	orifice flow area [$A_0 = \pi/4(d_0)^2$], in^2
A_1	water flow orifice or venturi pipe area (see Figure 4), in^2
A_2	water flow or venturi throat area (see Figure 4), in^2
C_D	flow discharge coefficient, d'less
C_1	weight scale calibration factor, lb_f/volt
C_2	linear potentiometer calibration factor, lb_f/volt
C_T	turbine meter calibration constant, GPM/Hz
d_0	water aperture diameter (see Figure 16), in.
d_2	orifice or venturi throat diameter (see Figure 4), in.
f	turbine meter frequency signal, Hz
g	acceleration of gravity, 32.2 ft/sec^2
h(t)	fluid height (Torricelli experiment), in.
H	height of aperture above ground plane (Torricelli experiment), in.
p_n	pressure at location n (n = 0,1,2,3 ...), psia
ΔP	pressure differential across an orifice or venturi, psid
Q_{CALC}	calculated water flow rate for orifice or venturi, GPM
Q_{IDEAL}	ideal water flow rate for orifice or venturi, GPM
Q_T	water flowrate measured by turbine meter, GPM
R	range or trajectory of water jet, in.
R_e	Reynolds Number based on a diameter, d'less
S_1	weight scale voltage signal, volts
S_2	linear potentiometer voltage signal, volts

Δt	time interval, sec.
V_J	water jet velocity (Torricelli Experiment), ft./sec.
V	air velocity (air flow tunnel), ft./min.
w(t)	water weight as a function of time (Torricelli experiment), lb_f
γ	specific weight, lb_m/sec.
υ	dynamic viscosity, ft.^{2}/sec.

Introduction

The Mechanical Engineering Technology major at Central Washington University features a laboratory component for almost all courses offered within the major. One such course, MET 315, Fluid Mechanics, is taught as a 5-credit hour course (quarter system) which meets for four hours of lecture and two hours of lab per week.

The students normally work in groups of two or three, depending upon the complexity of the experiment. This pooling of energy and knowledge is beneficial to the student. As in industry, the team approach is utilized so the student gets accustomed to collective working and thinking. Each experiment is concluded with a complete lab report which states objectives; lists equipment used; shows a schematic of the experiment, and contains data tables, sample calculations, conclusions, and recommendations. The recommendations are passed on to the next class who then act on the recommendations to make improvements to the experiment.

Although the students perform a series of six experiments during the quarter, this paper describes three of the more interesting and unique laboratory experiments. The experimental facilities discussed in this paper have all been built by MET students at a relatively low cost and fully tested over the last several years. Design details and approximate costs are presented in the paper so that others may benefit from our experiences. The paper contains a set of test data from each experimental facility so that the reader may judge the effectiveness of the experiment. All of the experiments performed with these facilities utilize state-of-the-art instrumentation and data systems, most of which have been donated by local industry. The students extensively utilize computers for data storage and processing using spread sheets.

The experience gained at CWU in the use of these facilities has been very positive in terms of comments and performance by our students, many of which are non-traditional. Fluid Mechanics taught at the Engineering Technology level can be greatly enhanced by utilizing a well thought out set of laboratory experiments crucial to the successful learning of the subject.

Water Flow Measurements Loop

A water flow facility having sufficient flexibility to perform numerous experiments was developed to support the Fluid Mechanics course. The facility supports experimentation to give the student an understanding in the underlying theory and practice of liquid flow measurements. Specifically, this lab teaches how to use a rotameter, venturi, orifice and turbine flow meter to measure flow rate and insertion loss. In another experiment, the facility is used to characterize the systems 20 hp centrifugal pump and associated flow controls. The facility has also been used to support various Senior Projects and in addition has been used to perform contract work.

Figure 1 shows the flow test loop schematically. The flow system is comprised of (1) a 500 gallon supply tank, (2) a liquid level sensor, (3) a 20 hp Berkeley centrifugal pump with an 8½ in. impeller and matching electric motor, (4) a Speedstar variable speed controller, (5) two flow monitoring rotameters, (6) a test section where various flow meters can be inserted, (7) various pressure gages, (8) a water temperature sensor, (9) system valves (inlet, throttling, bypass, backpressure, and fill), and (10) filters. Pump speed can be varied from 0 to 3500 RPM by controlling the motor's shaft speed using the Speedstar which connected to a 3 phase, 440 volt supply. Figure 2 is a photograph of the water flow measurements loop test facility.

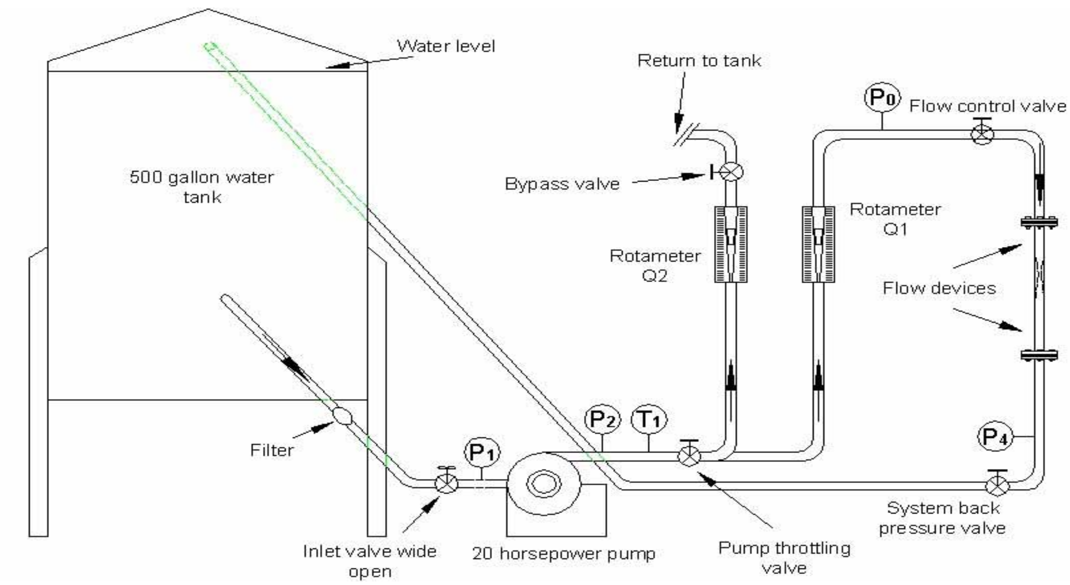


Figure 1. Schematic representation of the water flow measurements loop.

Figure 2. Photograph of the water flow measurements loop

Figure 3 shows details of the sharp-edged orifice, venturi, and turbine flow meters that are used in the experiments. The sharp-edged orifice meter is commonly used because of its simplicity, low cost, and standardization. One major drawback in practice is that it has a rather large insertion loss (pressure loss). However, there are many applications where a large insertion loss is of no consequence. The sharp-edged orifice is a flat piece of metal with a hole machined to precise dimensions according to ASME standards. Wear from long term usage causes abrasion of the precise dimensions and changes its discharge coefficient.

The venturi meter has a smooth entrance and exit cone and produces a well formed streamlined flow through the meter. As a result this meter has a much lower insertion loss and holds its calibration much better than the orifice. The venturi meter was also fabricated to ASME Standards. Venturi meters can handle larger flows at high Reynolds Numbers and maintain their discharge coefficient for longer periods. These meters are more costly than orifice meters and occupy more space. The following equations are used to calculate both orifice and venturi performance. Figure 4 defines the variables in equations (1) –(3) in terms of a venturi but they apply to the orifice as well. Figures 5 through 7 shows plots of flow versus delta P, insertion loss versus flow rate and discharge coefficient versus Reynolds Number for the orifice and venturi. The results of these experiments indicate clearly that the venturi will flow greater quantities of water for a given supply pressure with a lower ΔP and lower insertion loss. The discharge coefficients for the orifice and venturi agree well with published data [1].

$$C_D = Q_{ACT}/Q_{IDEAL} = Q/A_2 \cdot [1 - (A_2 / A_1)^2]^{1/2} \cdot [\gamma / (2g\Delta P]^{1/2} \quad \text{.........................(1)}$$

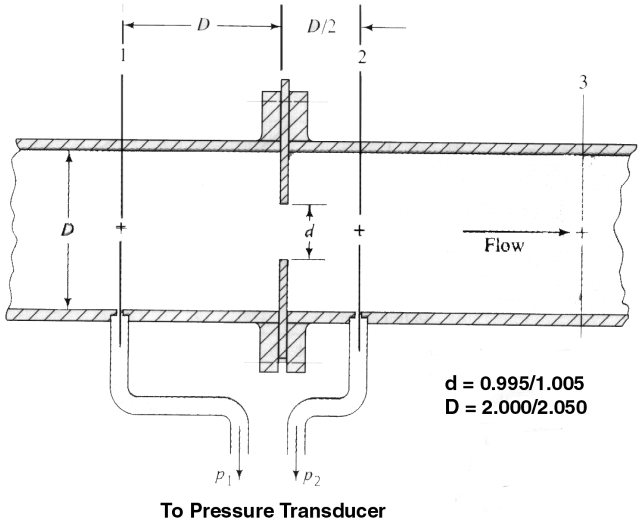
$$R_E = (Q_{ACT} / A_2) \cdot (d_2/\nu) \quad \text{...(2)}$$

$$\text{Insertion Loss} = P_3 - P_4 \quad \text{.. (3)}$$

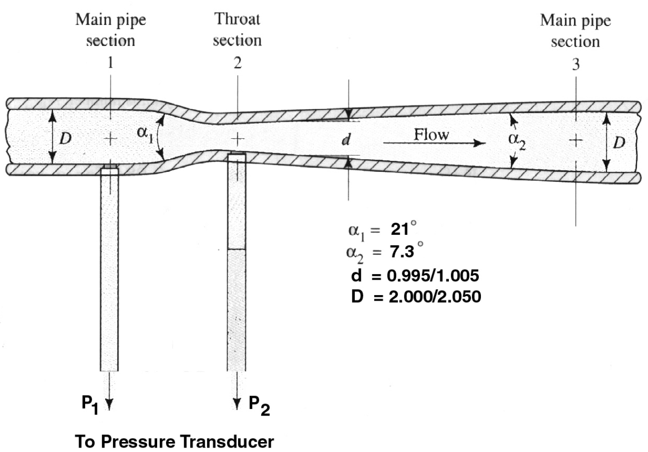
The turbine-type flow meter works on the momentum principle. It consists of a free-running small turbine suspended in a pipe. The rotation speed of the turbine is proportional to the volumetric flow rate. More specifically, the turbine flow meter consists of a straight pipe, a free-running multi-bladed turbine wheel suspended by two bearings, upstream and downstream flow straightners, and a magnetic pickup. The pickup gives one voltage pulse for each blade passing the pickup. Thus flow rate is a function of frequency and yields a linear relationship. The advantage of turbine flow meters is that they have very low insertation losses, reasonably high accuracy and have a high operating range (10:1) instead of 5:1 for a venturi or orifice. The relevant equations to assess turbine flow meter performance are given below. Turbine flow meter test data is plotted in Figure 8 which demonstrates the linear relationship between flow rate and frequency.

$$Q_T = (C_T) \cdot f \quad \text{...(4)}$$

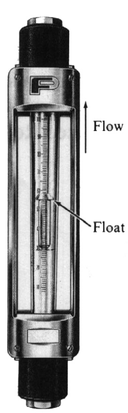
$$\text{Insertion Loss} = P_3 - P_4 \quad \text{.. (5)}$$



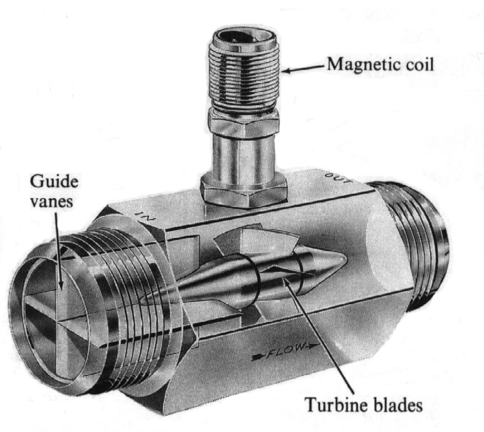
3a. Orfice meter details.



3b. Venturi meter details



3c. Rotameter



3d. turbine meter

Figure 3. Flow meter details

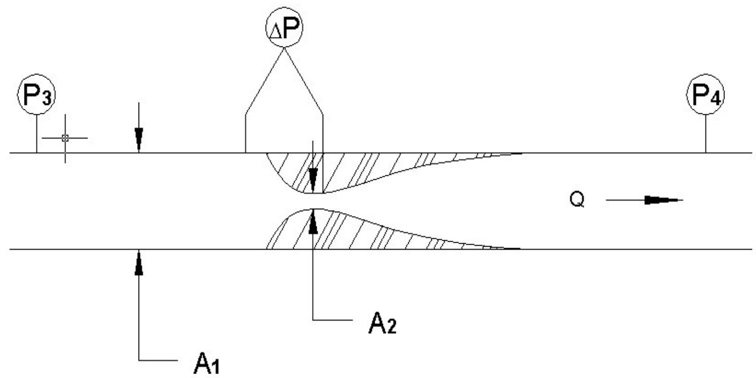


Figure 4. Definition of variables for the orifice and venturi.meters.

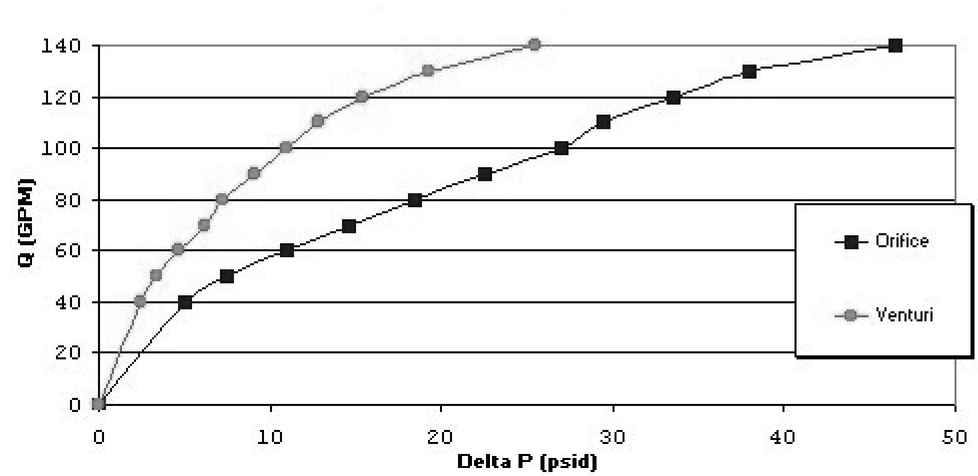


Figure 5. Flow vs. Delta P

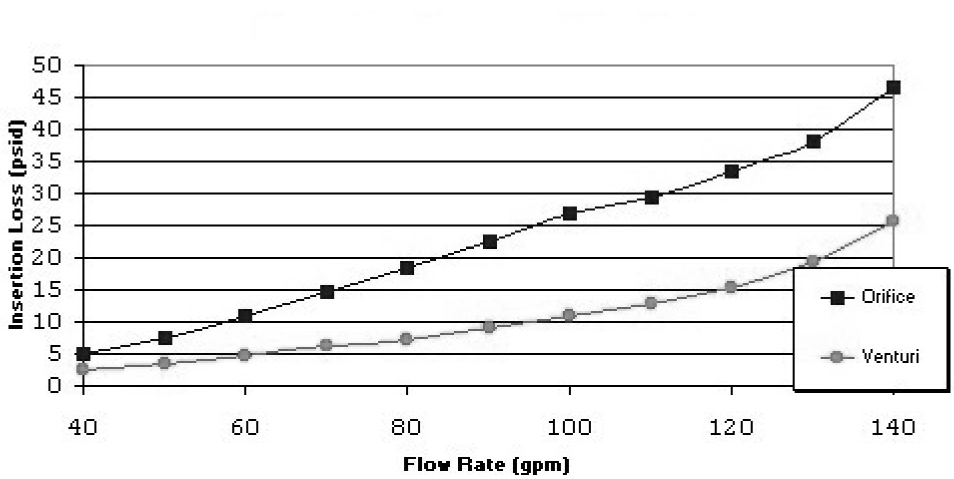


Figure 6. Insertion Loss vs. Flow Rate

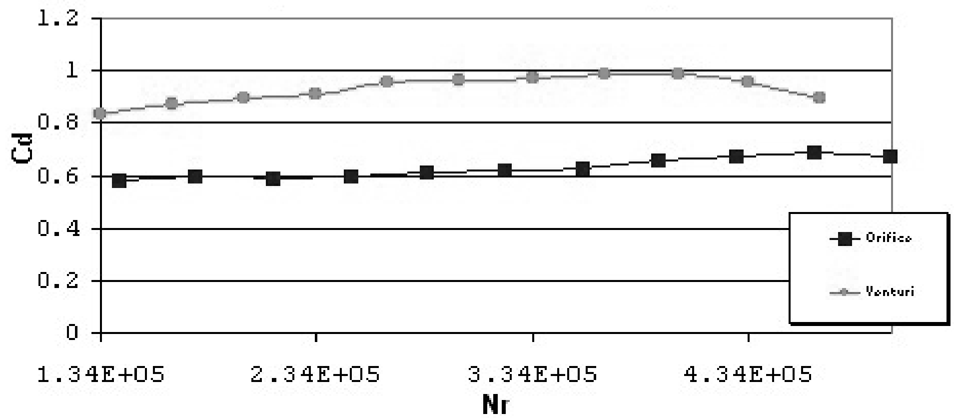


Figure7. Discharge Coefficient vs Reynolds Number

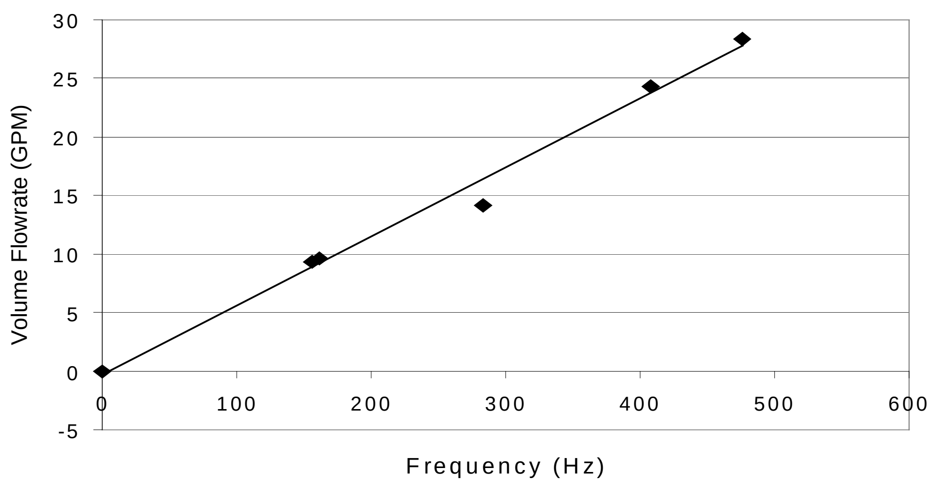


Figure 8. Turbine flowmeter performance

In another experiment, the students characterize the 20 hp. centrifugal pump for performance. The pump is operated over a range of shaft speeds ranging 2000 – 3500 RPM while throttling the outlet of the pump to vary the flowrate through the pump. Figure 9 displays the pump's performance.

The cost to duplicate the water flow measurements facility is approximately $3,700. This cost does not include labor. It is estimated that an experienced technician would require approximately 90 hours of labor. Our facility was mainly constructed with student labor with the exception of the electric hookup of the 20 hp motor and the Speedstar controller.

Six Inch Air Flow Tunnel

The MET student is expected to be able to measure and evaluate gas flow properties as well as liquid flows. For this reason, an air flow tunnel was designed and constructed as a cooperative

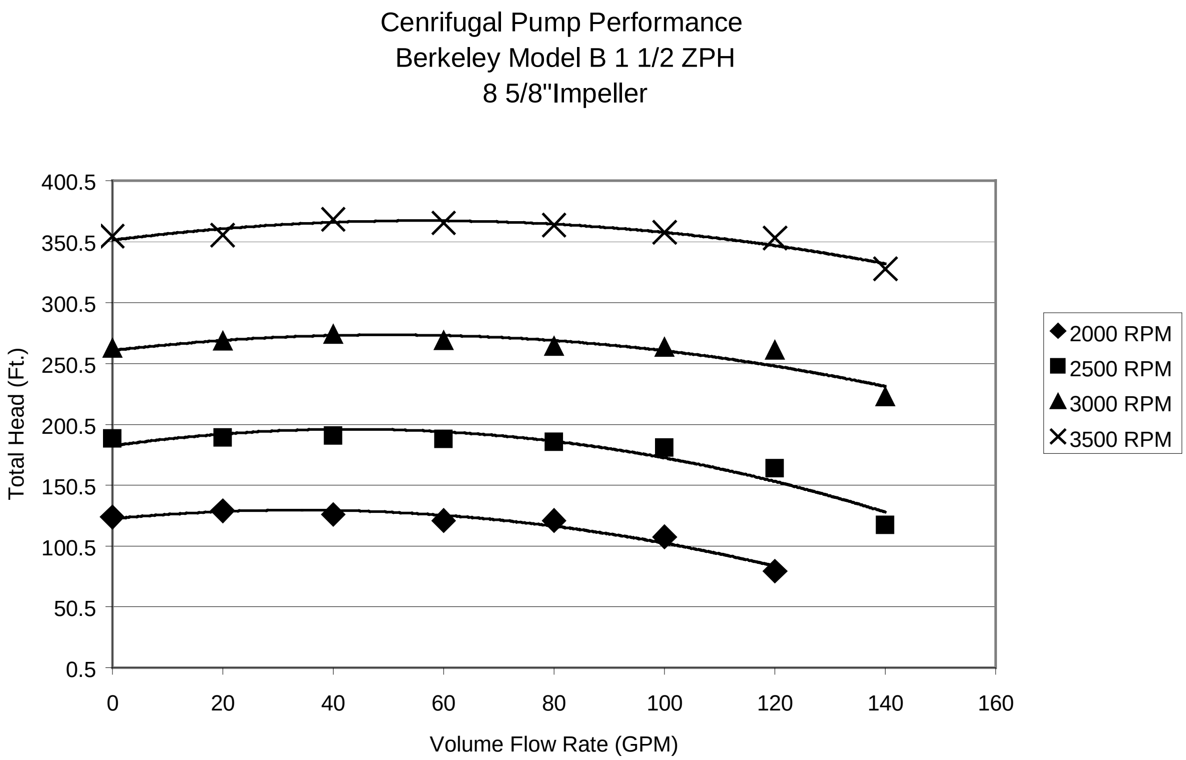


Figure 9. Centrifugal pump performance characteristics.

effort between a faculty member and his students. Although a primative version of the air flow tunnel was available for use after the first year of construction, the final configuration of this project took approximately 5 years to complete. Each succeeding class added features and made improvements to the facility.

The purpose of this facility is to allow students to perform experiments that teach them how to measure velocity, pressure, temperature and turbulence of a flowing air stream. Secondly, the students have the opportunity to observe air flow patterns in straight and convergent ducts as well as elbow turns. Other Senior Project experiments are planned for this facility to study external flow patterns, forces and turbulence levels. The facility is very flexible and has the capability of serving many purposes.

A schematic of the airflow tunnel is shown in Figure 10 and a photograph in Figure 11. The tunnel is comprised of a squirrel cage fan driven by a 1/3 hp electric motor operating on 220 volts. A Danfoss variable speed drive is incorporated into the system allowing the fan speed to vary. This allows the tunnel to be operated at variable air velocities. Interconnecting 6 in. PVC pipe of the type that local irrigators use has been incorporated into the design for cost reduction purposes. A bellmouth inlet supplies air to the fan with minimum losses and disturbance. The radial flow which discharges the fan is captured by a scroll case which in turn is connected to a conical diffuser. At the discharge of the diffuser, the air still has a strong radial component in addition to a forward velocity. The radial component is removed by using a flow straightening section made from a tightly packed bundle of 10 in. long drinking straws. This technique of straightening the flow has proved to be very effective in terms of performance and cost. At the exit of the tunnel, a pitot tube or hot wire anemometer probe[2] is mounted on a two axis translation stage shown in Figure 12. The probe can be translated very precisely by using a pair of computer controlled stepper motors. When the pitot probe is used, the differential pressure signal is fed into a sensitive electronic pressure transducer and recorded on a Fluke Hydra or directly into the computer using a DAQ card. When the hot wire probe is used, the resultant electronic signal is fed into a TSI anemometer for signal processing and then is stored in either a Fluke Hydra or directly into the computer. Data analysis is performed using spread sheet software.

Figures 13, 14 and 15 show velocity profiles and other measured parameters for the straight tube, nozzle and elbow test sections respectively. The velocity profiles for the straight duct and nozzle vary by approximately 10%. The velocity profiles for the elbow show an interesting trend. There is a negative velocity region near the inside curved portion of the elbow. This area was further investigated by using tufts of cotton fibers which showed an inflow to a separated region just past the inner curvature of the elbow as shown in Figure 15. The hot wire anemometer is our newest addition and has not as yet been fully tested. An initial test with the
hot wire aligned with the duct centerline indicated a turbulence level of 5.5% (V_{FLUCT}/V_{MEAN}).

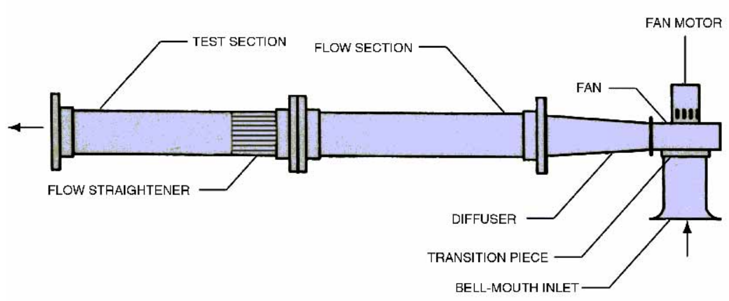


Figure 10. Schematic of airflow tunnel.

Figure 11. Photograph of airflow tunnel showing computer to control experiment.

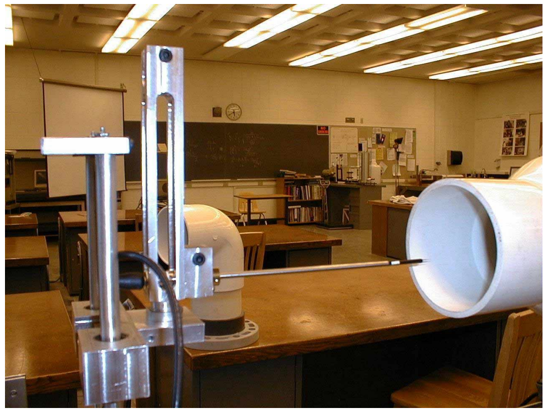
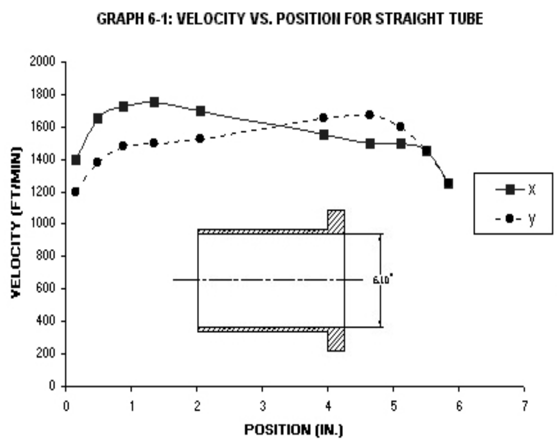


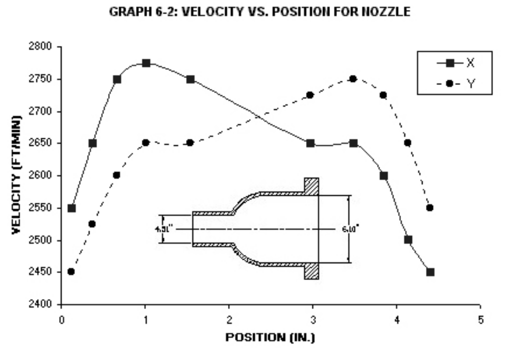
Figure 12. Photograph of two axis translation stage showing attached hot wire probe.

The cost to duplicate the air flow measurement facility is approximately $4,200. Student labor is not counted into the estimate but could be as high 200 hours. Much of the hardware was taken from surplused equipment including the computer which was extensively modified for use with the air flow tunnel. The computerized stepper motor controls were designed , fabricated, and made operational by a senior MET student as a Senior Project.



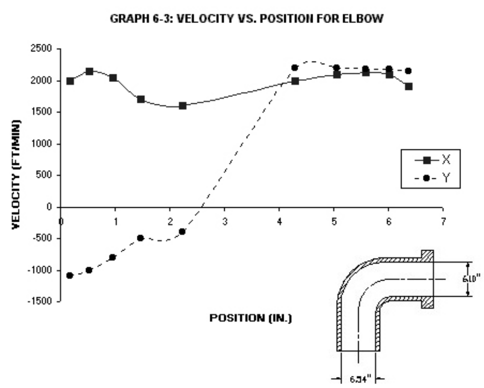
BAROMETER READING (IN. Hg)	FLOW TEMP INITIAL (°F)	FLOW TEMP FINAL (°F)	CENTER VELOCITY (FT/MIN)	AVERAGE VELOCITY (FT/MIN)	VOLUME FLOWRATE (CU FT/MIN)
29.29	72	73.2	1600	1508.75	297.23

Figure 13. Flow measurements made for straight duct



BAROMETER READING (IN. Hg)	FLOW TEMP INITIAL (°F)	FLOW TEMP FINAL (°F)	CENTER VELOCITY (FT/MIN)	AVERAGE VELOCITY (FT/MIN)	VOLUME FLOWRATE (CU FT/MIN)
28.88	73.8	73.2	2675	2630	291.8

Figure 14. Flow measurements for nozzle.



BAROMETER READING (IN. Hg)	FLOW TEMP INITIAL (°F)	FLOW TEMP FINAL (°F)	CENTER VELOCITY (FT/MIN)	AVERAGE VELOCITY (FT/MIN)	VOLUME FLOWRATE (CU FT/MIN)
28.88	73.8	73.2	1800	1341	312.9

Figure 15. Flow measurements made for the elbow.

The Torricelli Experiment

The Torricelli experiment is a classical experiment [3], performed countless times over many years at various technical institutions. However, though it is very simple in principle, it can be embellished in such a way as to demonstrate many fluid mechanical principles. Using electronic based instrumentation and data storage systems, it can provide excellent quantitative results that can be matched almost exactly by theory. This is very satisfying to a beginning engineering or technology student.

The Torricelli experiment involves time variation of all major parameters such as water height, flow rate, aperture velocity, range or effluent stream trajectory, and aperture discharge coefficient. The objective of the experiment is to study the effect of flow from a reservoir with a falling head. This experiment provides the student with an opportunity to obtain experience in the following areas:

1. Flow rate measurement using the most basic technique, the timed-weight method.
2. The effect of various types of aperture geometries: (a) smooth and rounded, (b) sharp edge orifice, and (c) inward projecting tube on rate of flow and time to empty.
3. Flow patterns (laminar/turbulent) as the fluid jets through an aperture at the bottom of the tank.
4. Use of electronic instrumentation and automated data collection systems.

Figure 16 shows a schematic of the Torricelli experiment whereas Figure 17 shows a photograph of the actual experimental facilities that was employed in the experiment. The tank used is a standard chemistry lab Nalgene 20 liter carboy. Water height is measured using a float assembly connected to the

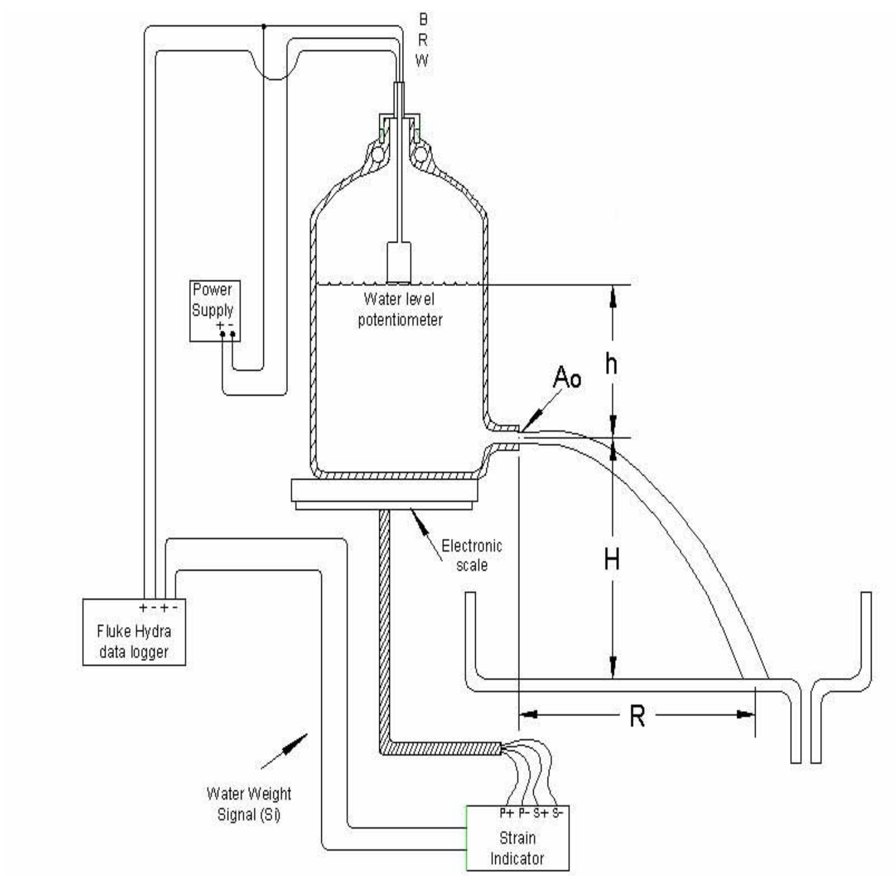


Figure16. Schematic drawing of the Torricelli experimental facility.

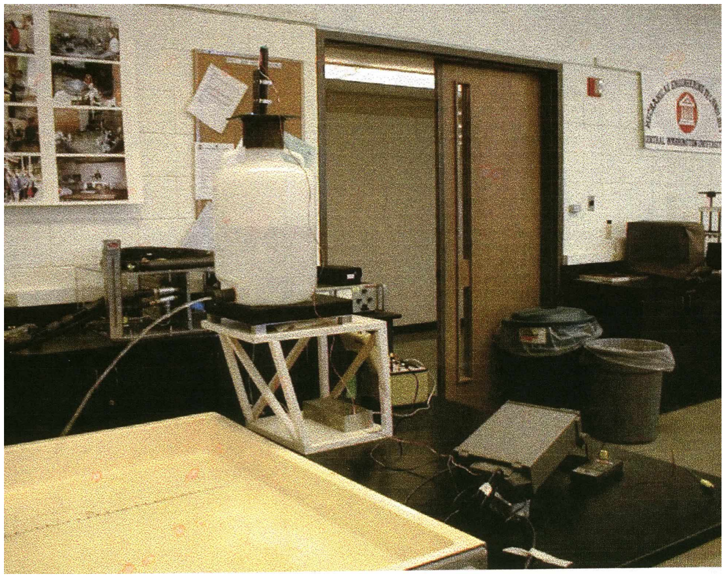


Figure 17. Photograph of the Torrecilli experimental facility under test conditions

center rod of a 12 in. linear potentiometer which is fixed to the tank by means of a heavy plate. When the height of water decreases due to efflux of water, the potentiometer voltage change is recorded by a Fluke Hydra set to make measurements at specified time increments. Thus the time variation of water height is determined. Water flow rate is measured by recording the weight of the water tank using a very sensitive strain gage weight scale (also fabricated by our students).

The separate outputs of the scale strain gages are converted to a single voltage signal using a Measurements Group Inc. P3500 strain indicator. Thus water flow rate is determined by introducing the weight scale signals into the Fluke Hydra. The range or trajectory of the water jet issuing from the tank aperture is measured by recording distance with a scale and time using a stop watch. This is the only non-automated measurement, but with care it is adequate for purposes of the lesson.

In these experiments, three separate aperture configurations are investigated; they include a sharp edged orifice, a smooth well rounded tube, and an inward projecting tube, each having the same diameter. The experiment is performed three times, using each different aperture. The student can then observe the variation of discharge coefficient on all parameters and correlate the flow pattern observations with aperture Reynolds Number. The relevant equations and constants for this experiment are stated below.

$$w(t) = S_1(t) \cdot C_1 \quad \text{(6)}$$

$$h(t) = S_2(t) \cdot C_2 \quad \text{(7)}$$

$$Q_{MEAS} = \Delta w(t)/\Delta t \cdot (1/\gamma) \quad \text{(8)}$$

$$V_J = [2gh(\Delta t)]^{1/2} \quad (9)$$
$$Q_{CALC} = A_0 \cdot V_J \quad (10)$$

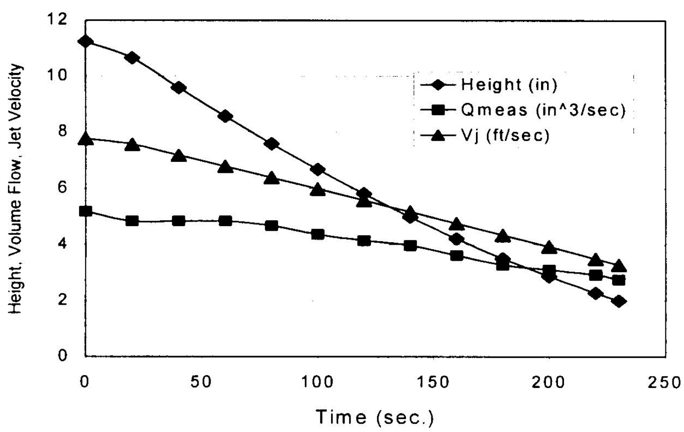
$$C_D = Q_{MEAS}/Q_{CALC} \quad (11)$$

$$N_R = V_J \cdot d_0/\nu \quad (12)$$

$$R = V_J \cdot \Delta t \quad (13)$$

Figure 18 shows measured data for water height, weight flowrate, and jet velocity as a function of time for the sharp edged orifice. Also shown is the variation of discharge coefficient as a function of orifice Reynolds Number. If theoretical [3] calculations are made, it becomes clear that there is good agreement between the measured and predicted values of all parameters.

The Torrecelli experimental facility can be duplicated for a cost of about $750 assuming that a data logger such as a Fluke Hydra is available.



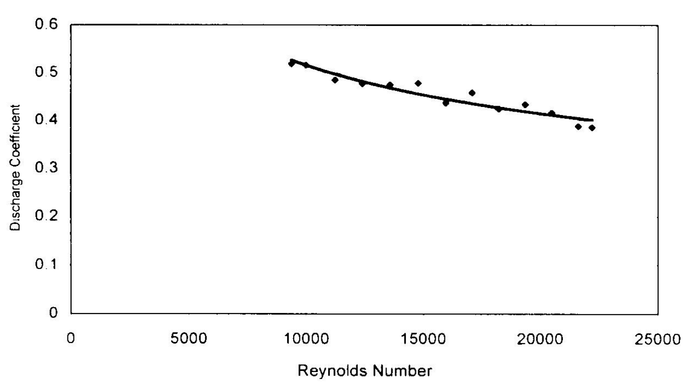


Figure 18. Experimental results of Torrecilli experiment.

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2. Jana, William S., Introduction to Fluid Mechanics, 3 rd ed., pp. 552-561, PWS-Kent, Boston,MA, 1993
3. Mott, Robert L., Applied Fluid Mechanics, 5th ed., pp. 171-172, Prentice Hall, Upper Saddle River, NJ, 2000

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