

**CHE 253M**  
**Experiment No. 3**  
**LIQUID FLOW MEASUREMENT**

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The objective of this experiment is to familiarize the student with several types of flow-measuring devices commonly used in the laboratory and in industry while performing calibration procedures. The experiment is designed to study uniform water flow over a range of flow rates.

The system consists of a pipe of several meters plumbed in series. There is an inlet water valve, an air pipe operated water flow control valve, a magnetic inductive flowmeter, a turbine flowmeter, a rotameter, an ultrasonic flowmeter, an orifice meter, and a venturi meter. The experimental setup is shown in Figure 1. The water that exits this pipe will be collected for known time intervals to obtain the standard flow rate, against which other devices will be calibrated. A dye injection system is included in the pipe to allow visual observation of the flow regime, i.e., whether the flow is laminar, turbulent, or transitioning between the two.

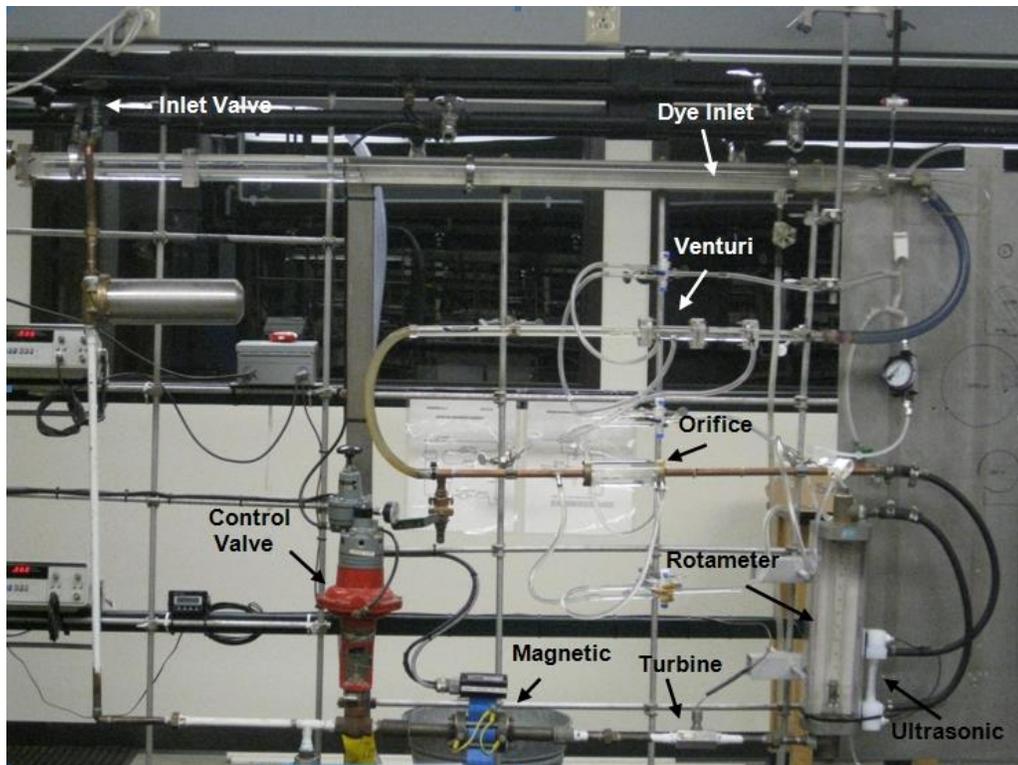


Figure 1. A picture showing the piping loop and the location of flowmeters.

## THEORY

### **The Primary Standard**

In order to calibrate the flow meters used in this lab, you must compare the output of the various flow meters to that of a primary standard. The output of the primary standard is considered the “true” volumetric flow rate passing through the system. For this lab, you and your group will come up with and implement a method using a graduated cylinder and a stopwatch to measure the volumetric flow rate passing through the system. These data will serve as your primary standard. While there is no “100% correct method” for taking these flow rate measurements, please use what you know about measurement uncertainty to devise the best possible method. In your lab write-up (in the results/discussion section) please discuss your procedure and the logic you used to arrive at such a technique.

### **Magnetic-Inductive Flowmeter**

Figure 2 shows the schematic structure of a magnetic flowmeter. This meter operates on the basis of the fact that when a conductive fluid (water in this case) flows through a magnetic field, a voltage is induced in the fluid. The induced voltage is proportional to the magnetic field strength, the fluid conductivity, and the velocity of the fluid (and thus the volumetric flowrate,  $Q_v$ ).

For processes in which the working fluid’s conductivity is not changed and the instrument’s configuration is held constant, the voltage is proportional to fluid velocity only. In this experiment, the magnetic meter measures the voltage and converts the output to a pulse rate (pulses per second or Hertz). The pulse rate is displayed on the pulse counter in units of kHz. Magnetic flow meters are generally expensive but highly accurate. They do not require a flow restriction. They are useful only for conducting fluids.

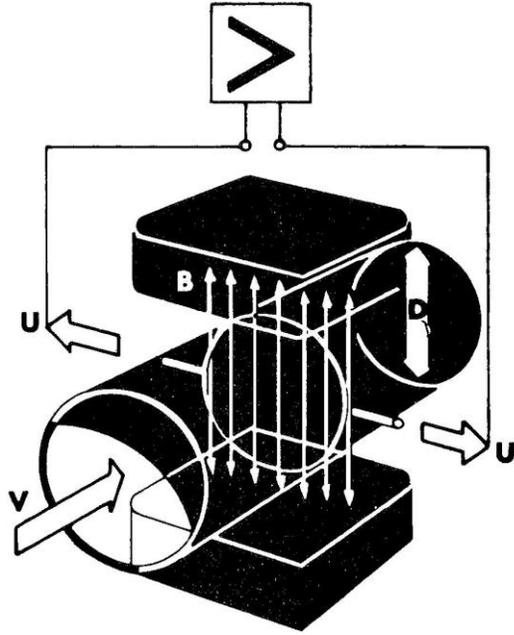


Figure 2. Schematic structure of a magnetic flowmeter. A magnetic field  $\mathbf{B}$  is generated by field coils.  $D$  is the pipe diameter. When a conductive fluid travels with a velocity  $\mathbf{v}$  through the magnetic field, a voltage  $U$  is induced:  $U = K (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{D}$ , where  $K$  is an instrument constant.

### Turbine Meter

A diagram of a turbine meter is shown in Figure 3. A turbine-type vaned rotor is placed in the path of the fluid flow. The rotational motion of the rotor is proportional to the rate of flow and is sensed by a reluctance-type pickup coil. A permanent magnet is encased in one or all of the rotor vanes. Each time the vane passes the pole of the coil, the change in the permeability of the magnetic circuit produces a voltage pulse at the output terminal. The pulse rate is counted by a frequency meter or any other suitable type of counter. The count rate is calibrated against the flow rate and is usually linear over a range of flow rates. For flow rates from 0 – 150 cc/sec the manufacturer has provided following calibration empirical relationship between the volumetric flow rate passing through the meter and the output frequency:

$$Q = U_T * f$$

In this equation  $Q$  is the volumetric flow rate in cc/sec,  $U_T$  is the universal Therman constant,  $\sim 107 \text{ cm}^3/\text{kHz sec}$ , and  $f$  is the output frequency in Hz. Turbine meters are generally expensive and they are accurate if the composition, temperature etc. of the flowing liquid remain constant, but they are subject to wear and are only useful for particle-free fluids.

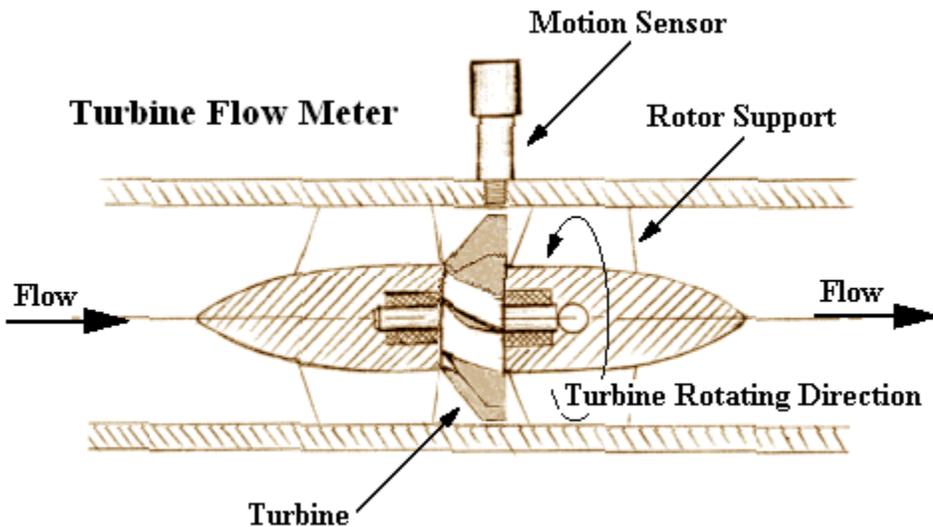


Figure 3. Cross-sectional view of a turbine flow meter

### Rotameter

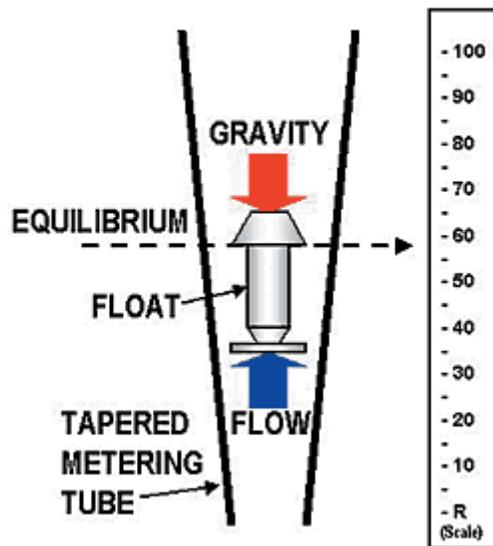


Figure 4. Schematic diagram of a rotameter.

The rotameter offers the advantage of a wide range of flow rates that can be directly measured. It is a variable-area meter with a float moving freely in a tapered tube. Figure 4 shows the structure of rotameter. For each flowrate, the float is lifted to some point at which the upward and downward forces acting on it are in equilibrium. As a fluid moves upward through the tube, the float acts as an obstruction and creates a pressure drop (also see orifice and venturi meters). This pressure drop and the buoyancy of the float (which may be positive or negative) produce an upward force on the float which is balanced by the gravitational force. The pressure force is dependent on the flow rate and the annular area between the float and the tube. As the float rises, the annular area increases, thereby requiring a larger flowrate to maintain the float position. The basic equation for the

rotameter can be developed in a manner similar to that for the orifice meter, as shown by Equation (3):

$$Q = A_w C \left( \frac{2gV_f(\rho_f - \rho_w)}{A_f \rho_w} \right)^{1/2} \quad (3)$$

where,

Q	=	volumetric rate of flow, ft <sup>3</sup> /sec
V <sub>f</sub>	=	volume of the float, ft <sup>3</sup>
ρ <sub>f</sub> , ρ <sub>w</sub>	=	density of the float and the fluid, lbm/ft <sup>3</sup>
A <sub>f</sub> , A <sub>w</sub>	=	area of the float and the annular orifice, ft <sup>2</sup>
C	=	discharge coefficient

The value of A<sub>w</sub> varies with the position of the float due to the taper in the tube. The meter can be calibrated, and typically a scale is shown that directly gives the flowrate. Rotameters are usually not very expensive and their accuracy depends largely on quality of construction.

The rotameter output is given in % max flow, where the maximum flow for this meter is 3.6 gpm when ρ = 1g/cm<sup>3</sup> and μ = 1 cP.

### **Orifice and Venturi Meters**

These two meters belong to a class of meters called obstruction meters. The obstruction meter acts as an obstacle placed in the path of the flowing fluid, causing localized changes in velocity and, consequently, in pressure. At the point of maximum restriction, the velocity will be the maximum and the pressure the minimum. Part of this pressure loss is recovered downstream as the velocity energy is changed back into pressure energy. Figure 5 shows the structure of an orifice meter and a venturi meter.

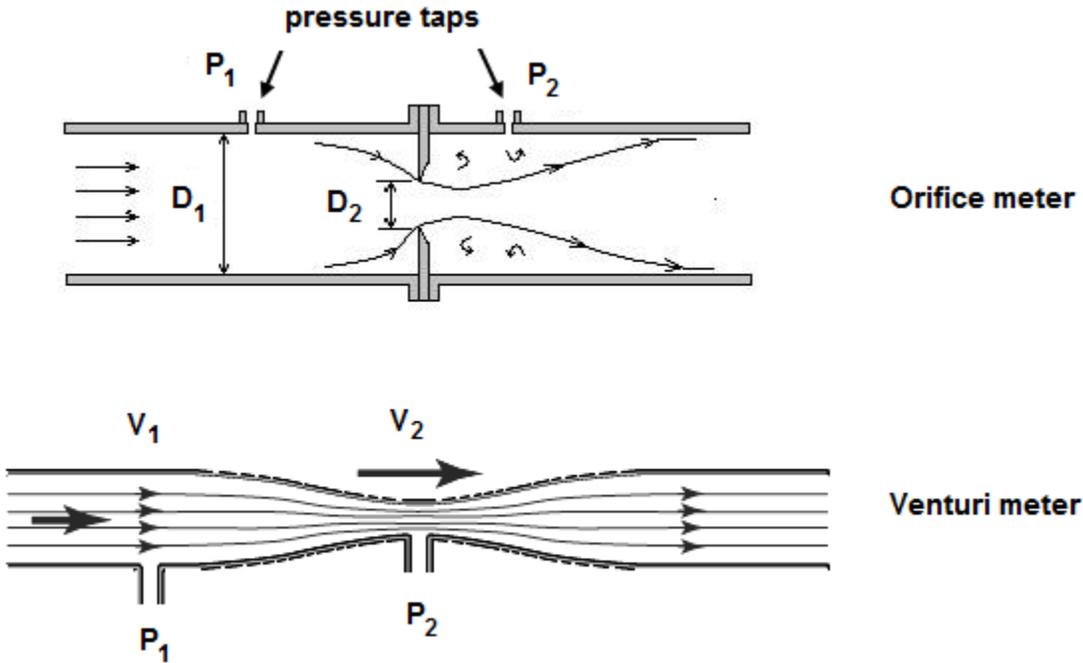


Figure 5. Diagrams illustrating orifice and venturi meter structure.

The nature of the liquid flow, i.e. laminar or turbulent, is described by the dimensionless number called the Reynolds number,  $Re$ , which is given by Equation (4) for flow in a cylindrical tube.

$$Re = \frac{\rho V D}{\mu} \quad (4)$$

where,

- D = inside diameter,
- $\rho$  = liquid density,
- V = linear velocity, and
- $\mu$  = viscosity

The basic equation for calculating the pressure drop through an orifice or venturi is the mechanical energy balance known as the Bernoulli equation. If subscript 1 refers to the upstream conditions and subscript 2 to the downstream conditions at the points of pressure measurement, then the Bernoulli equation is written as:

$$\frac{P_1}{\rho_1} - \frac{P_2}{\rho_2} = \frac{(V_2^2 - V_1^2)}{2g_c} + \frac{(Z_2 - Z_1)g}{g_c} \quad (5)$$

where,

- P = pressure of fluid
- $\rho$  = density of fluid
- V = linear velocity
- Z = elevation above some reference level
- g = acceleration due to gravity
- $g_c$  = gravitational constant in English units = 32.174 (lb<sub>m</sub> ft)/(lb<sub>f</sub> s<sup>2</sup>)

For a liquid, which of course is incompressible, the density is constant. If the meter is mounted on a horizontal pipe, (Z<sub>2</sub> - Z<sub>1</sub>) will be zero. If Q is the volumetric flow rate of the liquid, continuity implies that Q = A<sub>1</sub>V<sub>1</sub> = A<sub>2</sub>V<sub>2</sub>, where A<sub>1</sub> and A<sub>2</sub> are the cross-sectional areas at points 1 and 2.

From Equation (5) and the equation of continuity,

$$Q_{ideal} = V_2 A_2 = A_2 \sqrt{\frac{2g_c (P_1 - P_2)}{\rho_1 [1 - (A_2/A_1)^2]}} \quad (6)$$

(Please try to deduce this equation as an exercise.)

In practice, however, the value of Q calculated from the above equation differs from that actually measured due to irreversibilities (frictional losses). We define a discharge coefficient of an orifice or a venturi meter as:

$$C = \frac{Q_{actual}}{Q_{ideal}} \quad (7)$$

The working equation for orifices is then:

$$Q_{actual} = CA_2 \sqrt{\frac{2g_c \Delta P}{\rho(1 - \beta^4)}} \quad (8)$$

where  $\beta$  is the ratio of the diameter of the orifice to the diameter of the pipe (D<sub>2</sub>/D<sub>1</sub>).

The value of C varies with Reynolds number and  $\beta$  for a given orifice plate. Usually the range of an obstruction meter is limited by the range of the pressure difference that can be measured. The usual solution is to use an orifice or venturi of a certain size for a fairly narrow range of flow rates.

Orifice and venturi meters cause some permanent loss of pressure due to the turbulence they induce. The magnitude of this permanent pressure loss is dependent on  $\beta$ ,  $Re$ , and the type of orifice design. This permanent pressure loss is determined by measurement of the pressure before the orifice and the pressure far downstream of the orifice.

Orifice meters are cheap but cause a high pressure drop, resulting in high fluid pumping costs. Venturi meters are somewhat higher in cost because of more detailed machining required, but the associated pressure loss is lower than that for orifice plates.

### Ultrasonic Flowmeter

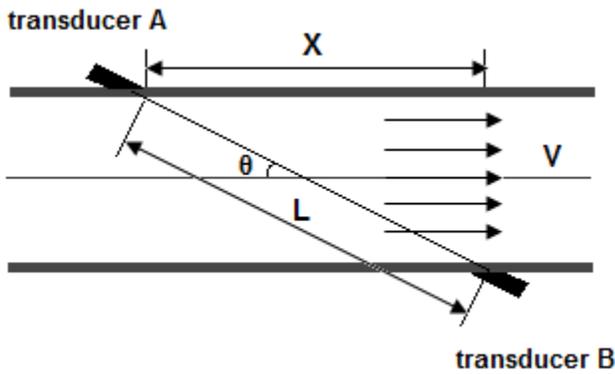


Figure 6. Structure of ultrasonic meter

An ultrasonic flowmeter is illustrated in Figure 6. This flowmeter measures the flow based on the difference in the time it takes for an ultrasonic wave to travel upstream as opposed to downstream. If  $t_d$  is the downstream transit time from A to B, and  $t_u$  is the upstream transit time from B to A, then

$$t_d = \frac{L}{c + V \cos \theta} \quad (9)$$

$$t_u = \frac{L}{c - V \cos \theta} \quad (10)$$

where  $L$  is the path length,  $X$  is the axial spacing between the transducers,  $c$  is the speed of sound in the liquid,  $V$  is the average linear velocity of the flow, and  $\theta$  is the angle between flow direction and sound transit direction. Note that  $\cos \theta = X/L$ . Solving equations (9) and (10) gives the flow velocity:

$$V = \frac{L^2 \Delta t}{2X t_u t_d} \quad (11)$$

where  $\Delta t = t_u - t_d$ . Because  $V$  is the average velocity, some small error may be incurred in the laminar flow regime due to the parabolic velocity profile.

## **EXPERIMENTAL PROCEDURE & CALCULATIONS**

### **Data on the Experimental Setup**

- orifice throat diameter : 0.20 inches
- venturi throat diameter: 0.25 inches
- pipe connected to the orifice: 0.55 inches
- pipe connected to the venturi: 0.50 inches
- pipe diameter at the dye injection: 1.75 inches

### Initial Setup

- 1) Open the water supply valve to the apparatus
- 2) Open the air supply valve to the control valve actuator
- 3) Connect the pulse counters to the magnetic flow meter and the turbine meter. Be certain that the discharge water hose is in the sink (or else - what a mess!).

### **Part A: Calibrate the magnetic flowmeter, turbine flowmeter, ultrasonic flowmeter and rotameter:**

- 1) Begin the calibration by setting the water flow to read 90% of the max flow you can achieve on the rotameter. Use the graduated cylinder and stopwatch as your primary standard to measure the volumetric flow rate passing through the system.
- 2) Reduce the water flow rate in 3-4 even steps to a minimum of 10% of max flow on the rotameter. Record readings for the turbine meter, magnetic meter, rotameter, ultrasonic meter and, of course, your primary standard.
- 3) Convert readings taken with the bucket and stop watch to  $\text{cm}^3/\text{sec}$ .
- 4) Plot the rotameter readings (in percent of max flow) vs. the bucket/stopwatch readings (in  $\text{cm}^3/\text{sec}$ )
- 5) Determine least squares equations for the rotameter.

**Part B:** Calibrate the orifice plate and the venturi, assume that the rotameter is now the absolute standard.

- 1) Calculate water flows required to produce Reynolds numbers of 8,000, 13,000, and 18,000 through the orifice and venturi meters. **Do these calculations before you come to class.** Assume a density for water of  $1.000 \text{ g/cm}^3$ . You will need to adjust this calculation to reflect the measured temperature of the water and corresponding density of the water you use in the experiment. Record what other assumptions went into these calculations.
- 2) Back calculate the readings required on the rotameter (in percent of max flow) to achieve the above flows by using the least squares equation.
- 3) Set the flows such that the rotameter reads what you calculated in Part B-2 above. Measure  $\Delta P$  across orifice plate itself and also downstream of the orifice plate using the pressure gauges and/or manometer (Blue Fluid specific gravity = 1.75). **DO NOT turn the pressure gauge toggle counter-clockwise.** Move from the least sensitive to most sensitive gauge.
- 4) Repeat steps 2 through 3 for the venturi flowmeter.

**Part C:** Visual Determination of the Onset of Turbulence:

- 1) Ensure that the burettes are filled with a food coloring.
- 2) Back calculate the reading required on the rotameter to achieve  $35.0 \text{ cm}^3/\text{s}$  flow by using the least squares equation. Adjust the flowrate such that the rotameter reads what you calculated. Describe the characteristics of laminar flow.
- 3) Back calculate the reading required on the rotameter to achieve  $200.0 \text{ cm}^3/\text{s}$  flow by using the least squares equation. Adjust the flowrate such that the rotameter reads what you calculated. Describe the characteristics of turbulent flow.
- 4) Decrease the water flowrate slowly, and determine the point at which transitional (random) motion begins to affect the dye pattern downstream of the injection. Record rotameter readings once both transitional flow and laminar are detected.
- 5) Repeat starting from laminar flow conditions and then increasing the flow rate. Record rotameter readings once both transitional flow and turbulent flow are detected.

*Note:* At low Reynolds numbers the flow is laminar, as may be judged by watching a plume of dye injected into the pipe. The plume travels straight with the liquid for some distance without being disturbed or mixed with the rest of the liquid. At high Reynolds numbers the flow is turbulent, and the dye is instantly mixed with the rest of the liquid near the point of injection. The approximate transition Reynolds number in a pipe is  $\sim 2100$ .

## RESULTS

1. Discuss the procedure and the logic you used to arrive at the technique you ended up using to measure the flowrates with the primary standard (the bucket and stopwatch method).
2. Show the calibration equations for the magnetic flow meter, turbine flow meter, ultrasonic flowmeter, and the rotameter versus the bucket/stopwatch primary standard. Report your results in the form  $y = mx + b$ , where  $x$  is the flow rate,  $y$  is the instrument output, and  $m$  and  $b$  are the slope and intercept, respectively. Report the 95% confidence limits on  $m$  and  $b$  for all four meters. Also include the calibration plots of the rotameter, turbine meter, ultrasonic meter, and the magnetic meter.
3. Which is the most precise: the rotameter, ultrasonic meter, magnetic flow meter, or turbine meter based on the precision standard discussed in lecture (confidence limits)?
4. Compare the accuracy of the ultrasonic meter, turbine meter, and the rotameter by comparing them against the bucket/stopwatch standard. In order to compare accuracies, all meter outputs must be in the same units. What is the flaw in this accuracy test? Which meter is best at low flow rates and which is best at high flow rates? Discuss your observations.
5. Calculate the discharge coefficient for the orifice and venturi meters at  $Re = 8,000, 13,000, \text{ and } 18,000$ . Determine and report the permanent pressure loss for both instruments at these Reynolds numbers. Were your results expected, and how do these values generally compare to results from literature? Which instrument, based on your measurements, would result in lower pumping costs? Explain using the discharge coefficient and permanent pressure drop data.
6. Describe your observations for laminar and turbulent flow. Report the transitional Reynolds number range you observed. Discuss the difficulties in defining the transitional range in terms of the physics of the experiment. Why is this a difficult measurement to make?
7. Discuss sources of error in this experiment. What could be done to improve the experiment?
8. Include your sample calculations. This section should show the formulas for linear regression and confidence intervals, but the summations do not have to be carried out by hand. You should show the “ $t$ ” value for the confidence interval calculations. Include other appropriate sample calculations such as the required flowrates for the specified Reynolds numbers, the discharge coefficients, etc.

9. Research the function of a standard pressure regulator; use more than one source and cite them using the APA style or ACS style (if a journal reference). Describe how this device works. How does the regulator control the downstream pressure of a fluid? What are some limiting cases where the regulator might fail to perform as expected?