The Design of a Fluid Meters Apparatus for the Fluid Mechanics Laboratory

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ABSTRACT – An inexpensive yet portable device for calibrating four different flow meters in the undergraduate fluid mechanics laboratory was designed and constructed. The apparatus contains a rotameter, a turbine-type meter, a venturi meter, and an orifice meter. All four meters are calibrated simultaneously using a volumetric measuring tank. Results obtained by undergraduate students are presented, and advantages of using this apparatus are described.

Keywords: meters, venturi, orifice, rotameter, turbine meter

INTRODUCTION

It has been known that laboratory instruction is an extremely valuable teaching tool, especially when integrated with a lecture course. Performing an experiment develops a student's ability to understand how equipment works, how to make measurements, and how to analyze experimental data.

The Fluid Mechanics Laboratory appears in many curricula, and complements the fluid mechanics course itself. Experiments are performed that parallel what is taught in the lecture course, and this practice is an excellent pedagogical tool. One important experiment performed in the laboratory is in the calibration of a meter in a pipeline.

There are a number of meters that are used to measure flow rate in a pipeline. To calibrate each and every one would involve weeks of work. So it is important to determine which meters to have in the laboratory, and to be able to calibrate them in as few sessions as appropriate.

In this study, an inexpensive, portable apparatus was constructed for calibrating four different rate meters using water as the fluid medium. The apparatus and the experiment was designed so that all four meters can be calibrated in one laboratory session by a group of three-to-five students. This approach allows data to be obtained on all meters simultaneously, and it exposes the students firsthand to more than just a single meter during one effective laboratory session.

Before performing the experiment, students are given a lecture about the four meters, and instructions on how to operate the apparatus as well as how to obtain data. They are also told what to submit as part of their report. Experience has shown that it is expedient to have the students submit a group report consisting of an introduction, raw data, reduced data, sample calculation, and pertinent graphs. In this way, the students will become familiar with meters in general, without a major expenditure of effort. Data provided in this study were obtained by students.

APPARATUS DESCRIPTION

Figure 1 is a schematic of the apparatus. It contains a 30 gallon (0.12 m^3) sump tank made of plastic, and used as a reservoir. A 3/4 hp (0.55 kW) pump takes water from this tank and moves it through a piping system. The pump discharge line contains a rotameter, a turbine-type meter, a venturi meter, and an orifice meter. The rotameter is made of glass by Cal-Q-Flow, with a range of 0 to 10 gpm (0 to 36 L/min). The turbine type meter is made of plastic, and manufactured by Blue-White Industries (model F-1000-RB), and reads in LPM. The venturi meter and the orifice meters are made of transparent Plexiglas, and manufactured by Technovate. (This company is now out of business.) After leaving the flow line that contains the meters, the water then goes to either the sump tank, or to a plastic volumetric measuring tank (10 gallon capacity, or 0.038 m^3).

Pipe/Fittings

The pipe is all schedule 80 PVC, and all joints are cemented together using PVC adhesive. The flow line from the pump to the rotameter is 3/4-nominal; and from the rotameter onward is 1-nominal.

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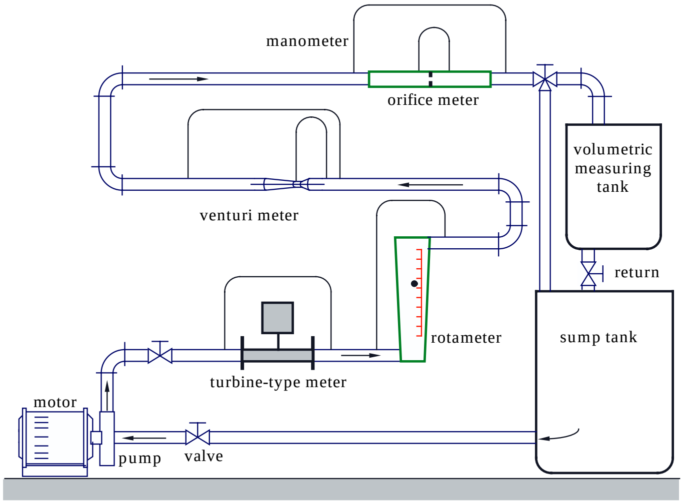


FIGURE 1A. SCHEMATIC OF THE FLUID METERS APPARATUS.

FIGURE 1B. FLUID METERS APPARATUS (1975).

FIGURE 1C. FLUID METERS APPARATUS (2010).

The pump has threaded fittings. The turbine-type meter has flanged fittings, and the rotameter has threaded fittings. The venturi and orifice meters are cemented to PVC couplings.

Pressure Measurement

Each meter has a pressure tap upstream and downstream of the fittings to illustrate and measure pressure recovery. The venturi and orifice meters have two additional pressure taps appropriately located to measure pressure drop within each meter. The pressure taps are connected with flexible tubing to a manometer board (not shown in Figure 1A). Manometer connections are indicated in the figure.

Frame and Mounting

The piping system is attached to a welded steel frame with U-bolts. Tanks are supported on their bottoms and with surrounding framework. The pump is mounted on vibration isolators, which are bolted to the steel frame. The steel frame itself is made of 1 x 1 in (2.5 x 2.5 cm) square tubing. The frame has 5 casters attached so that the entire apparatus may be moved about.

There are many different meters used in pipe flow. Each meter works by its ability to alter a certain physical characteristic of the flowing fluid and then allows this alteration to be measured. The measured alteration is then related to the flow rate. The meters used in this apparatus are the turbine type meter, the rotameter, the orifice meter, and the venturi meter. It is possible also to install an elbow meter, a nozzle meter, a nutating disk meter, and more. A procedure of analyzing and calibrating any number of meters in this apparatus is possible.

The Turbine-Type Meter.

The turbine-type flow meter consists of a section of pipe into which a small "turbine" has been placed. As the fluid travels through the pipe, the turbine spins at an angular velocity that is proportional to the flow rate. After a certain number of revolutions, a magnetic pickup sends an electrical pulse to a digital output electronic device, which gives a direct reading of the volume flow rate. Figure 2 is a schematic of the turbine type flow meter.

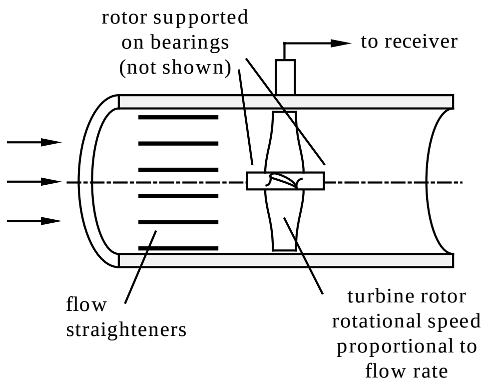


FIGURE 2. A SCHEMATIC OF A TURBINE-TYPE FLOW METER.

The Rotameter (Variable Area Meter)

The variable area meter consists of a tapered metering tube and a float which is free to move inside. The tube is mounted vertically with the inlet at the bottom. Fluid entering the bottom raises the float until the forces of buoyancy, drag and gravity are balanced. As the float rises the annular flow area around the float increases. Flow rate is indicated by the float position read against the graduated scale which is etched on the metering tube. The reading is made usually at the widest part of the float. Figure 3 is a sketch of a rotameter.

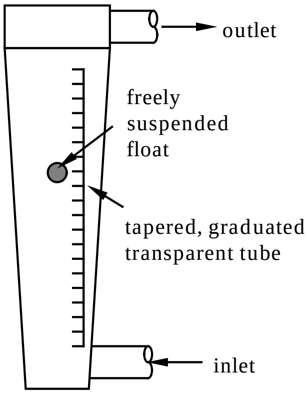
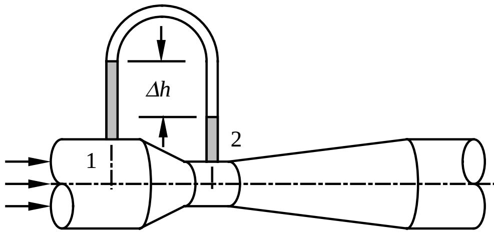


FIGURE 3. SCHEMATIC OF THE ROTAMETER.

The Venturi Meter

The venturi meter is constructed as shown in Figure 4. It contains a constriction known as the **throat**. When fluid flows through the constriction, it experiences an increase in velocity over the upstream value. The velocity increase is accompanied by a decrease in static pressure at the throat. The difference between upstream and throat static pressures is then measured and related to the flow rate. The greater the flow rate, the greater the pressure drop Δp. So the pressure difference Δh (= $\Delta p/\rho g$) can be found as a function of the flow rate.



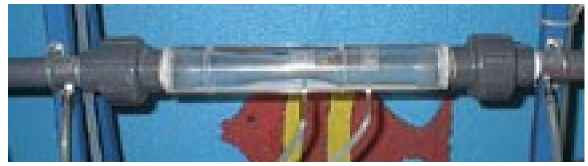


FIGURE 4. A SCHEMATIC OF THE VENTURI METER.

The Orifice Meter

The orifice meter consist of an orifice plate placed into the flow. (See Figure 5). Flow moving through the orifice plate creates a measurable pressure difference from upstream to downstream sections. The measured pressure difference is then related to the flow rate. Like the venturi meter, the pressure difference varies with flow rate.

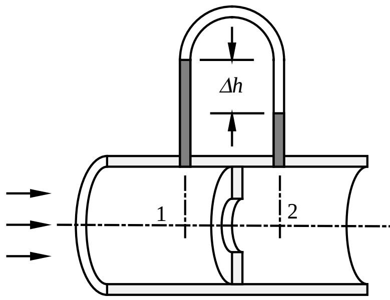


FIGURE 5. THE ORIFICE METER.

DATA

The pump is turned on and water flows through all four meters back to the sump tank. For one setting of the valve just downstream of the pump, and while the water is made to flow into the volumetric measuring tank, the following data are obtained:

Q_r = volume flow rate from the rotameter
Q_t = volume flow rate reading from the turbine type meter readout device
ΔH_r = head loss from upstream to downstream of the rotameter
ΔH_t = head loss from upstream to downstream of the turbine type meter
ΔH_v = head loss from upstream to downstream of the venturi meter
ΔH_o = head loss from upstream to downstream of the orifice meter
Δh_v = head loss within the venturi meter
Δh_o = head loss within the orifice meter
t = time required for the volumetric measuring tank to fill to a pre-determined volume

Experimental Results

The raw data obtained from the apparatus has been converted to SI units [3] and displayed in Table 1. The data shown were obtained by students during one laboratory session. The data in the Q_{ac} column was calculated by dividing the measured volume by time. Physical properties were obtained from [1]. Pipe dimensions may be found in [2].

A graph of volume flow rate as read from the **turbine-type meter** versus volume flow rate measured at the volumetric measuring tank is required, and is shown in Figure 6. A graph of volume flow rate as read from the **rotameter** versus volume flow rate measured at the volumetric measuring tank is required, and is shown in Figure 7.

TABLE 1. REDUCED DATA OBTAINED FROM THE FLUID METERS APPARATUS.

Data pt	Q_r x 10^{-5} m^3/s	Q_t x 10^{-5} m^3/s	ΔH_r m of H_2O	ΔH_t m of H_2O	ΔH_v x 10^{-3} m of H_2O	ΔH_o x 10^{-3} m of H_2O	Δh_v x 10^{-3} m of H_2O	Δh_o x 10^{-3} m of H_2O	Q_{ac} x 10^{-5} m^3/s
1	7.57	7.57	0.15	0.085	3.4	16.	6.4	0.011 2	6.75
2	10.1	10.7	0.19	0.13	4.9	24.	11.3	0.019	9.21
3	12.6	13.2	0.26	0.19	7.9	36.6	17.7	0.033 2	11.7
4	15.1	16.4	0.344	0.30	9.8	54.3	25.4	0.047 9	13.8
5	17.7	18.9	0.451	0.411	12.8	74.7	33.2	0.068 3	17.0
6	21.5	22.7	0.649	0.625	20.7	113.	52.4	0.109	20.8
7	27.8	29.7	0.948	0.994	31.7	187.	87.5	0.186	27.1
8	32.8	35.3	1.36	1.38	46.0	272.	130.	0.276	32.2
9	35.3	37.8	1.60	1.60	50.9	310.	143.	0.310	36.0

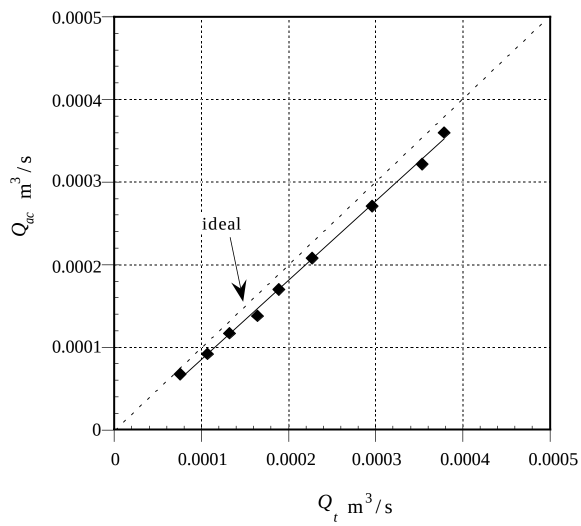


FIGURE 6. TURBINE METER CALIBRATION CURVE.

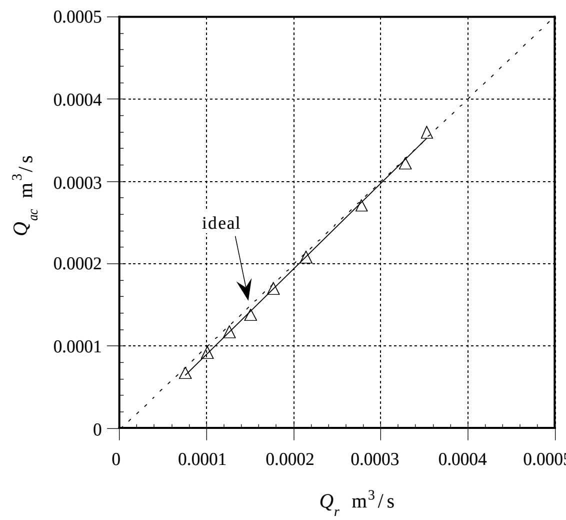


FIGURE 7. CALIBRATION CURVE FOR THE ROTAMETER.

The venturi and orifice meters require a bit more analysis [4]. For the **venturi meter**, the hydrostatic equation applied to the air-over-liquid manometer of Figure 4 gives the pressure drop in terms of the head loss (after simplification):

$$\frac{p_1 - p_2}{\rho g} = \Delta h$$

By combining the continuity equation,

$$Q = A_1 V_1 = A_2 V_2$$

with the Bernoulli equation,

$$\frac{p_1}{\rho} + \frac{V_1^2}{2} = \frac{p_2}{\rho} + \frac{V_2^2}{2}$$

and substituting from the hydrostatic equation, it can be shown after simplification that the volume flow rate through the venturi meter is given by

$$Q_{th} = A_2 \sqrt{\frac{2g\Delta h}{1 - (D_2^4/D_1^4)}} \tag{1}$$

The preceding equation represents the *theoretical* volume flow rate through the venturi meter, because it is derived from the Bernoulli equation, which does not take frictional effects into account.

In the venturi meter, there exists small pressure losses due to viscous (or frictional) effects. Thus for any pressure difference, the actual flow rate will be somewhat less than the theoretical value obtained with Equation 1. For any Δh, it is possible to define a coefficient of discharge C_v as

$$C_v = \frac{Q_{ac}}{Q_{th}}$$

For each and every measured actual flow rate through the venturi meter, it is possible to calculate a theoretical volume flow rate, a Reynolds number, and a discharge coefficient. The Reynolds number is given by

$$\mathbf{Re} = \frac{V_2 D_2}{\nu} \tag{2}$$

where V_2 is the velocity at the throat of the meter, based on the actual flow rate ($V_2 = Q_{ac}/A_2$). The venturi meter graphs are provided in Figures 8 and 9.

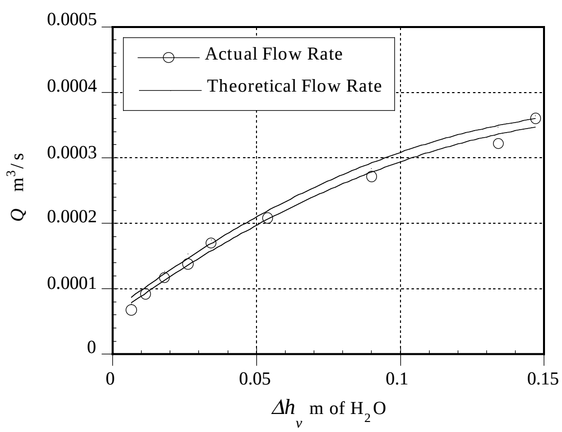


FIGURE 8. VENTURI METER CALIBRATION CURVE.

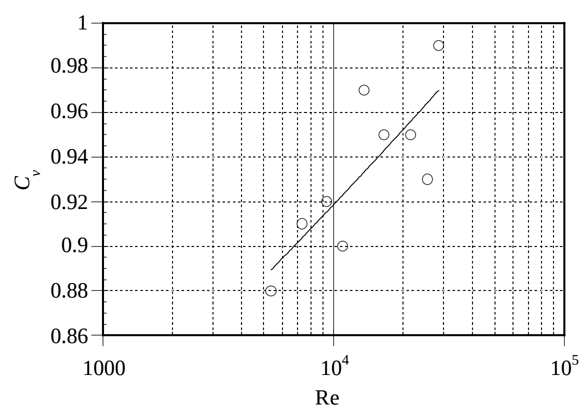


FIGURE 9. DISCHARGE COEFFICIENT VERSUS THROAT REYNOLDS CURVE FOR THE VENTURI METER.

The analysis of the **orifice meter** presents another problem. The measurement of pressure downstream is at a section that has the same diameter as the upstream location. However, there is a pressure drop, and it is usually related to the upstream diameter and the throat diameter. Applying Bernoulli's equation to points 1 and 2 of the orifice meter (Figure 4) yields the same theoretical equation as that for the venturi meter, namely, Equation 1 with the orifice diameter D_o in place of D_2. For any pressure difference, there will be two associated flow rates for this meter: the theoretical flow rate (Equation 1), and the actual flow rate (measured in the laboratory Q_{ac}). The ratio of actual to theoretical flow rate leads to the definition of a discharge coefficient: C_o for the orifice meter. The orifice meter graphs are provided in Figures 10 and 11.

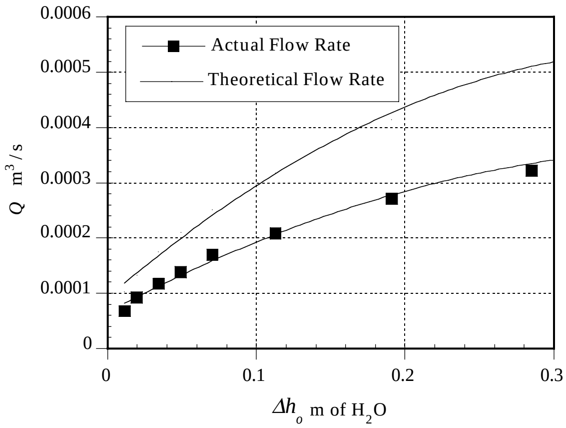


FIGURE 10. ORIFICE METER CALIBRATION CURVE.

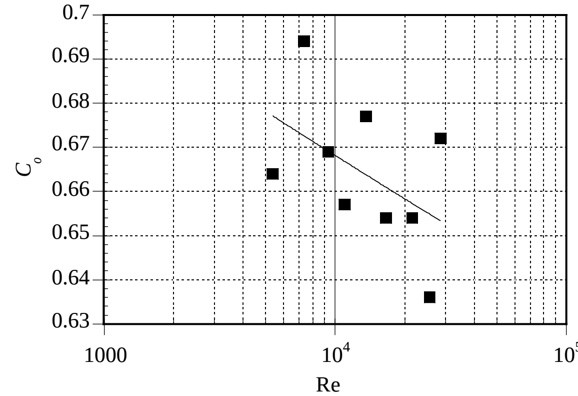


FIGURE 11. DISCHARGE COEFFICIENT VERSUS THROAT REYNOLDS CURVE FOR THE ORIFICE METER.

Pressure Coefficient

Note that the venturi meter has two manometers attached to it. The "inner" manometer is used to calibrate the meter; that is, to obtain Δh readings used in Equation 1. The "outer" manometer is placed such that it reads the *overall* pressure drop in the line due to the presence of the meter and its attachment fittings. We denote this pressure loss as ΔH (distinctly different from Δh for the orifice and venturi meters). This loss is also a function of flow rate. The manometers on the turbine-type and variable area meters also give the incurred loss for each respective meter. Thus readings of ΔH vs Q_{ac} are obtainable. In order to use these parameters to give dimensionless ratios, pressure coefficient and Reynolds number are used. The Reynolds number is given in Equation 2 with velocity based on downstream (of each respective meter) diameter. The pressure coefficient is defined as

$$C_p = \frac{g\Delta H}{\frac{1}{2}V^2} \tag{3}$$

All velocities are based on actual flow rate and pipe diameter. The pressure loss graphs are provided in Figures 12 and 13.

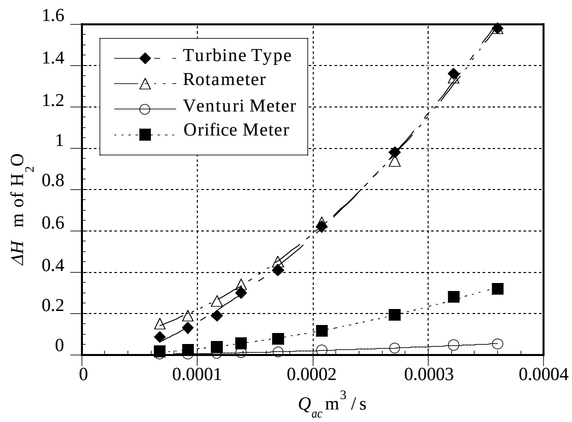


FIGURE 12. PRESSURE LOSS VERSUS ACTUAL FLOW RATE FOR ALL METERS.

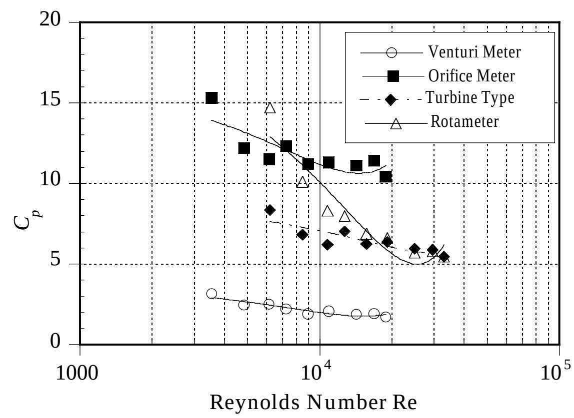


FIGURE 13. PRESSURE COEFFICIENT VERSUS PIPELINE REYNOLDS NUMBER FOR ALL METERS.

CONCLUSIONS AND RECOMMENDATIONS

A switch from engineering units to SI units may be the correct thing to do academically, but many industries have still not done so. It is therefore prudent to teach students both systems.

Plexiglas venturi meters are no longer available commercially. There are many manufacturers of this meter. It is recommended that two be purchased; one used for experimental purposes, and the other cut in half for demonstration purposes.

The advantage an orifice meter has over the others is that it can be made quite simply. A pipe can be cut and two flanges attached. An orifice plate can be inserted between the flanges. Pressure taps are attached and the meter may then be calibrated.

ASME has a very useful and practical text on venturi and orifice meters. The ASME has established construction standards and calibration information for these meters. It is prudent to adhere to ASME specifications and demonstrate how calibration curves can be generated for existing meters.

The apparatus described here is an extremely versatile device. It (and its predecessors) has been used for over 30 years to demonstrate concepts associated with fluid meters.

The apparatus is portable and considered “bench-top type.” The objective of having an apparatus this size is that the students are not overwhelmed by something much larger.

Pressure is measured with air-over-water manometers mounted on a manometer board. Although pressure transducers might be considered a better choice, students should be exposed at some point to manometers and to how they are used.

NOMENCLATURE

Variable	Definition	Dimension
A	Area	L^2
C_p	Pressure coefficient	dimensionless
D	Diameter	L
g	Acceleration due to gravity	L/T^2
p	Pressure	F/L^2
Q	Volume flow rate	L^3/T
Re	Reynolds number	dimensionless
t	Time	T
V	Velocity	L/T
ΔH	Head loss	L
Δh	Head loss Venturi or Orifice meter	L

Greek Letters		
ρ	Density	M/L^3
ν	kinematic viscosity	L^2/T

REFERENCES

[1] Bolz, R. E. and G. L. Tuve, editors. CRC Handbook of Tables for Applied Engineering Science, 2nd ed. Cleveland, OH: CRC Press.

[2] Dimensions in English units obtained from ANSI B36.10-1979, American National Standard Wrought Steel and Wrought Iron Pipe.

[3] Standard for Metric Practice. E 380–76. Philadelphia, PA: American Society for Testing and Materials.

[4] The American Society of Mechanical Engineers. Fluid Meters—Their Theory and Application. New York: The American Society of Mechanical Engineers.

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William S. Janna joined the faculty of The University of Memphis in 1987 as Chair of the Department of Mechanical Engineering. He served as Associate Dean for Graduate Studies and Research in the Herff College of Engineering. His research interests include boundary layer methods of solution for various engineering problems, and modeling the melting of ice objects of various shapes. He is the author of three textbooks, a member of ASEE and of ASME. He teaches continuing education courses in the area of piping systems and in heat exchanger design and selection, for ASME. Dr. Janna received a B.S. degree, an M.S.M.E. and a Ph.D. from the University of Toledo.