A Simple Sharp-edged Orifice Demonstration for the Fluid Mechanics Classroom

W. Roy Penney, Shannon L. Servoss, Christa N. Hestekin and Edgar C. Clausen
Ralph E. Martin Department of Chemical Engineering
University of Arkansas

Abstract

A simple and inexpensive sharp-edged orifice demonstration is described for use in the laboratory or Fluid Mechanics classroom. A steady-state demonstration is described which yields a discharge coefficient, C_D, of 0.64, almost identical to coefficients described in the literature. A time-dependent experiment employed C_D to yield model results which were within 3% of the experimental data obtained in draining water from the pipe through the orifice.

Keywords

orifice meter, sharp-edged orifice, Bernoulli balances, laboratory experiments, fluid mechanics

Introduction

Although students are motivated differently, have different preferences for how they learn and wish to be taught, and respond differently to various teaching techniques,[1] many engineering students are visual learners and do not respond well to instruction that is not engaging.[2, 3] Lin and Tsai[4] note that learning environments that are student-centered, peer-interactive and teacher-facilitated significantly help students in learning complex engineering concepts. The literature describes a number of techniques for engaging students in the classroom including the use of virtual engineering laboratories;[5] developing interactive, activity-driven classroom environments;[4, 6-8] relating the curriculum to real life problems[9] and even using games as teaching tools.[2]

Fluid mechanics has been a popular subject for classroom engagement, both in the laboratory and as classroom demonstrations. Fraser *et al.*[10] described the use of computer simulations to enhance both the classroom and laboratory experience. Wicker and Quintana[11] extended the use of fluid mechanics to the design and fabrication of lab experiments by the students, and Walters and Walters[12] used the combination classroom instruction and lab experience to introduce fluid mechanics to talented high school students. Loinger and Hermanson[13] used an integrated experimental-analytical-numerical approach in the teaching of fluid mechanics, and student surveys showed that 90% of their students preferred this re-designed class to the traditional lecture class, and also felt like they obtained a better understanding of the engineering fundamentals.

The most widely used flow measuring device in industry is the orifice meter. An orifice meter consists of an accurately machined and drilled plate, mounted between two flanges, with the hole most often set in the center of the pipe in which it is mounted (see Figure 1). Pressure taps, located upstream and downstream of the plate, are used to measure the pressure differential (see Figure 2), which is then used in calculating the flow rate. The most common orifice plate is the sharp-edged orifice, which is usually beveled on the downstream side and has a sharp edge on the upstream side (see Figure 3). The sharp-edge orifice is popular because of its low cost, simplicity, small size and the large amount of data available in describing its behavior and application.[14, 15] Orifice meters containing sharp-edged orifice plates that are designed with standard dimensions yield discharge coefficients with errors of only 0.4-0.8%.[15, 16]

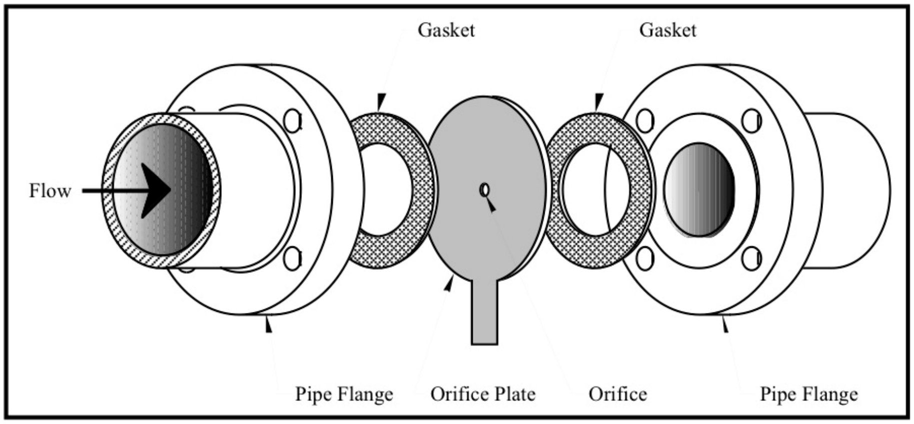

Figure 1. Placement of the Orifice Plate

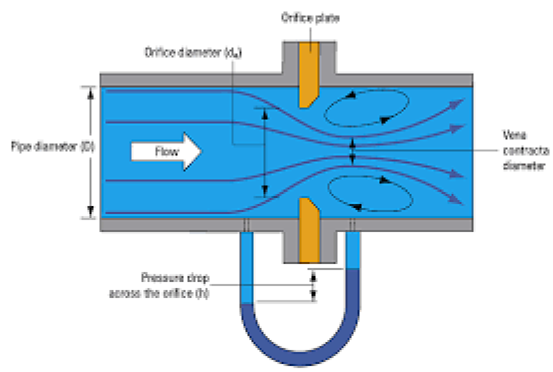

Figure 2. Operation of an Orifice Meter

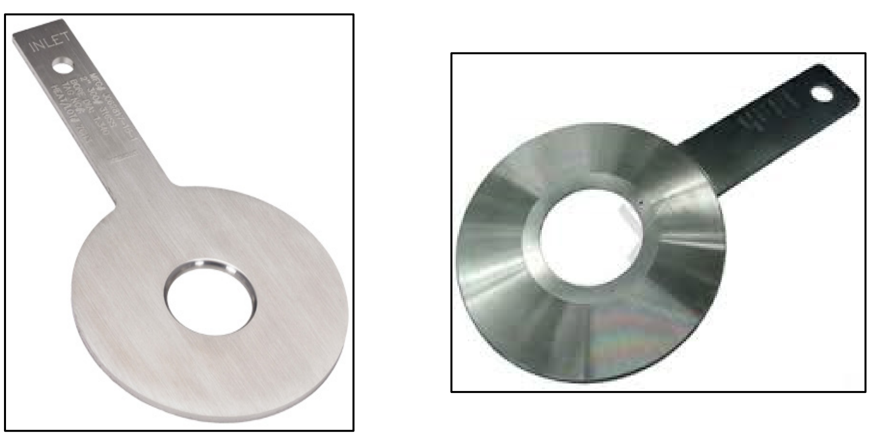

Figure 3. Sharp-edged Orifice Plates: upsteam (left), downstream (right)

The objective of this paper is to describe the construction of a simple experimental apparatus containing a sharp-edge orifice, followed by the presentation of results obtained when using this apparatus in a classroom demonstration to determine the coefficient of discharge (C_D) in a steady-state experiment. The experimentally determined C_D is then used to model the draining of the reservoir. This demonstration experiment is important educationally because:

- it requires students to correctly use a Bernoulli balance to model a steady state system, and a Bernoulli balance and mass balance to model a transient system.
- it shows the students that this simple apparatus can yield a C_D that is very close to the accepted value of 0.61-0.65[17] for sharp-edged orifices.

Experimental

Apparatus

A photograph of the experimental apparatus (and students participating in a classroom demonstration) is shown in Figure 4. The apparatus consisted of a 4 in (10.2 cm) inside diameter, 24.25 in (61.6 cm) long PVC pipe (0.25 in walls), containing the sharp-edge orifice at the bottom of the pipe, and attached upright to a metal support tripod. The PVC pipe had a sight glass tube (0.25 in clear PVC) attached to its side to observe liquid level in the pipe. A 17 gal (64 liter) utility tub was used to collect water flowing from the pipe, and Erlenmeyer flasks and graduated cylinders were used to hold, feed and collect water flowing in and out of the system. A stopwatch was used for timing the flow of water.

Figure 4. Photograph of the Experimental Apparatus

Figure 5 shows the PVC pipe from below, which shows the PVC plate containing the sharp-edge orifice (on the discharge side). The plate was fashioned from 0.5 in (1.3 cm) PVC, was 4 in

(10.2 cm) in diameter and had a 0.25 in (6.35 mm) orifice at its center. As was noted earlier, the orifice must be properly designed and constructed with standard dimensions to minimize the error in C_D. In this case, the orifice plate was machined with a 30° angle and a 0.020 in (0.5 mm) land, the minimum orifice wall thickness (see Figure 6).

Figure 5. Photograph of the Discharge of the Orifice, as Shown from the Tube Bottom

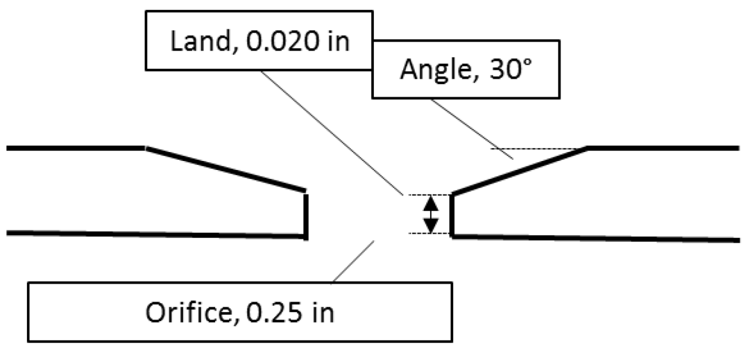

Figure 6. Design of Sharp-edged Orifice

Experimental Procedure

To begin an experiment, the entire apparatus (tripod, pipe and tube with orifice) was placed in the utility tub. The orifice was plugged with a short length of Tygon® tubing, and the pipe was filled with water. Additional water was made available, as needed, for the experiment. Five students were recruited to perform the experiment.

To execute a steady state experiment, the plug was first removed from the orifice. Water was continuously poured into the reservoir to maintain the liquid level at the very top. Once steady state was reached, in a few seconds, the water flowing through the orifice was collected in a 2,190 mL (volume completely filled to overflowing) Erlenmeyer flask. The time to fill the flask to overflowing was recorded. The plug was then replaced, and the experiment was repeated, as desired. To execute a time-dependent experiment, the arrangement was essentially the same, except that the water was allowed to drain with time (as opposed to maintaining a constant level) after removing the plug.

Experimental Data

Table 1 shows the raw experimental data for student-generated steady state experiments. Five runs were made collecting 2,190 mL of water. Results from a time-dependent run are shown in Table 2, as the height of the water in the tank as a function of time.

Table 1. Experimental Data for the Steady State Experiment

Run	Collection time, s
1	30.98
2	30.90
3	30.86
4	31.01
5	30.90

*the diameter of the pipe was 4.0 in (10.2 cm)

Table 2. Experimental Data for the Time-dependent Runs

Time, s	Fluid Height, cm
0	60.96
7.24	55.88
13.59	50.80
20.28	45.72
27.53	40.64
35.17	35.56
42.75	30.48
52.15	25.40
61.82	20.32
73.11	15.24
86.36	10.16
103.1	5.08
133.6	0

Model Development

The basic Bernoulli Balance, with no work in the system and negligible friction losses, is described by Wilkes *et al.*[18]

$$\frac{v_1^2}{2g} + z_1 + \frac{P_1}{\rho g} = \frac{v_2^2}{2g} + z_2 + \frac{P_2}{\rho g} \tag{1}$$

For application in this experiment, point 1 was selected as the fluid level in the pipe, and point 2 was selected as the location of the *vena contracta*, which is located one-half of an orifice diameter from the orifice entrance.[19] Since both ends of the tube were open to the atmosphere,

$p_1 = p_2$. The velocity at the top of the liquid in the pipe, v_1, may be neglected, and the *vena contracta* is at zero height, so that $z_2 = 0$. With these simplifications, Equation (1) may be rearranged to solve for v_2, the velocity at the *vena contracta*, v_{vc}:

$$v_2 = v_{vc} = \sqrt{2gz_1} \tag{2}$$

The C_D of the orifice may be described by the equation

$$Q = C_D A_2 v_{vc} \tag{3}$$

where A_2 is the area of the orifice, equal to $\frac{\pi d_o^2}{4}$. Thus, C_D may be calculated as

$$C_D = \frac{Q}{A_2\sqrt{2gz_1}} \tag{4}$$

for the steady state system, where the volumetric flow rate is calculated as the volume of water collected, divided by the time of collection ($Q = \frac{V}{t}$).

In considering the time-dependent system, the simplified Bernoulli balance of Equation (2) must be combined with the mass balance,

$$\frac{dm}{dt} = m_1 - m_2 \tag{5}$$

For a draining tank, $m_1 = 0$, since there is no water flowing into the tank. Furthermore, $\frac{dm}{dt}$ may be written as $\rho A \frac{dh}{dt}$, and m may be written as $\rho v A$. Thus, Equation (5) becomes

$$\rho A_1 \frac{dh}{dt} = -\rho v_2 A_2 \tag{6}$$

Combining Equations (2) and (6) yields

$$\frac{dh}{dt} = -\frac{A_2}{A_1}\sqrt{2gh} \tag{7}$$

Separating variables and integrating Equation (7) from $h = h_0$ at $t = 0$, and $h = h$ at $t = t$ yields, with rearrangement

$$h = \left(\frac{C_D t A_2 \sqrt{2g}}{-2A_1} + \sqrt{h_0}\right)^2 \tag{8}$$

Finally, taking the square root of each side yields

$$\sqrt{h} = \frac{C_D t A_2 \sqrt{2g}}{-2A_1} + \sqrt{h_0} \tag{9}$$

Thus, a plot of $\sqrt{h}$ vs. t will yield a straight line, the usual method of presenting this type of data.

Reduced Results and Discussion

Steady-State Results

The average volumetric flow rate was calculated from the experimental data in Table 1 (Q = 7.085 m^3/s) and combined with the geometrical variables (A_2 = 3.17E-5 m^2, z_1 = 24.375 in [0.610 m]) in Equation (4) to yield a C_D of 0.641. Wilkes *et al.*[18] note that the discharge coefficient should be about 0.63 for these operating conditions (Re_o = 14,000). This agrees well with the experimental value from the steady state runs of 0.641.

Time-dependent Results

Figure 7 shows plots of $\sqrt{h}$ vs. t for the experimental data and the model prediction from Equation (9). The drain time predicted by the model agreed very well with the experimental data, within about 3%, except for the last data point.

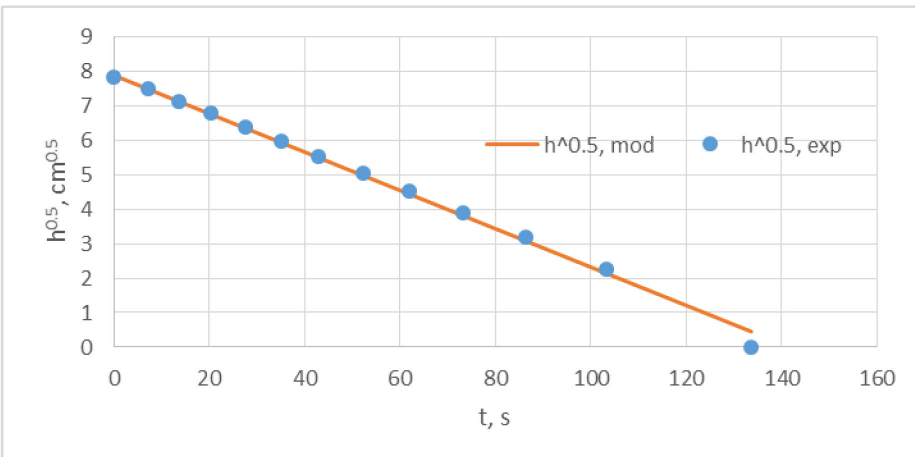

Figure 7. Plot of Time-dependent Experimental Data with the Model Prediction of Equation (9)

Educational Use and Value

The sharp-edge orifice demonstration/experiment has been used with success in junior-level Fluids and Heat Transfer Laboratory and in sophomore-level Fluid Mechanics. A typical class size for Fluid Mechanics is 60-80 students per semester. After tank draining had been covered in lecture, the time-dependent experiment was performed in class with students recording all the relevant data. Student groups then used the data and the equations learned in class to calculate C_D. The students were asked to prepare a report which discusses the assumptions made in their calculations and their appropriateness. Once the report was graded and returned, an in-class discussion addressed poor assumptions such as a pseudo-steady state assumption for the time-dependent experiment.

Although there was no formal assessment of the value of this activity in the classroom, all instructors reported anecdotal student comments that the exercise was very useful in improving their understanding of orifice construction and the measurement of discharge coefficients. Formalized assessment will be a focus of this activity in the future.

Conclusions

1. The experiment is an excellent teaching tool because it shows students how a sharp-edged orifice must be machined, and applies the Bernoulli and mass balances to reduce experimental data and develop a tank draining model.
2. The well-designed orifice yielded discharge coefficients which were almost identical to those described in the literature, with errors of about 3%.
3. This experiment meets all the requirements of a well-designed classroom experiment:
    - The apparatus is inexpensive
    - The experiments can be easily and quickly conducted in the classroom
    - Fundamental principles can be applied to model the experiment
    - The experimental results agree with literature data
    - The experimental data and model predictions are easily compared using linear plots; agreement is excellent

Nomenclature (SI units shown)

Latin Symbols

A	Area, m^2
A_1	Area of the PVC pipe, 0.0081 m^2
A_2	Area of the orifice, 3.17 x 10^{-5} m^2
C_D	Orifice discharge coefficient, dimensionless
d_o	Diameter of orifice, 0.0064 m (0.25 in)
g	Gravitational constant, 9.8 m/s^2
h	Height of the liquid in the tank or pipe, m
h_o	Initial height of the liquid in the tank or pipe, m
m	Mass, kg
m_1	Mass of water entering the pipe, kg
m_1	Mass of water entering the pipe, kg
$p_1 = p_2$	Pressures at top of liquid in the pipe and at exit of orifice, kPa
Q	Volumetric flow rate, m^3/s
t	Time, s
t_e	Time to empty the tank or pipe, s
V	Volume of water collected from apparatus, m^3
v	Velocity, m/s
v_1	Velocity at the top of the water in the pipe, m/s
$v_2 = v_{vc}$	Velocity leaving the orifice; velocity in the *vena contracta*, m/s
z_1	Height of water in the pipe, m
z_2	Height of water at the orifice, arbitrarily set a 0 m

Greek Symbols

ρ	Density of water, 1000 kg/m^3
μ	Viscosity of water, 0.1 kg/m·s

Dimensionless Groups

Re_o	Reynold's number through the orifice, $\frac{d_o v_2 \rho}{\mu}$, dimensionless

Acknowledgment

The authors acknowledge the skills of Mr. George Fordyce in machining the orifice to specifications.

References

1. Felder, R., and R. Brent, "Understanding Student Differences," *Journal of Engineering Education*, 94 (1), January 2005, 57-72.
2. Bodnar, C.A., D. Anastasio, J.A. Enszer and D.D. Burkey, "Engineers at Play: Games as Teaching Tools for Undergraduate Engineering Students," *Journal of Engineering Education*, 105 (1), January 2016, 147-200.
3. Pomales-García, C., and Y. Liu, "Excellence in Engineering Education: Views of Undergraduate Engineering Students," *Journal of Engineering Education*, 96 (3), July 2007, 253-262.
4. Lin, C.C., and Tsai, C.C., "The Relationship Between Students' Conception of Learning Engineering and Their Preference for Classroom and Laboratory Learning Environments," *Journal of Engineering Education*, 98 (2), 193-204, April 2009, 193-204.
5. Mosterman, P.J., M.A.M. Dorlandt, J.O. Campbell, C. Burow, R. Burow, A.J. Broderson and J.R. Bourne, "Virtual Engineering Laboratories: Design and Experiments," Journal of Engineering Education, 83 (3), 279-285, July 1994.
6. Kresta, S., "Hands-on Demonstrations: An Alternative to Full Scale Lab Experiments," Journal of Engineering Education, 87 (1), 7-9, January 1998.
7. Bidanda, B., and R.E. Billo, "On the Use of Students for Developing Engineering Laboratories," Journal of Engineering Education, 84 (2), 205-213, April 1995.
8. Carr, R. D.H. Thomas, T.S. Venkataraman, A.L. Smith, M.A. Gealt, R. Quinn and M. Tanyel, "Mathematical and Scientific Foundations for an Integrative Engineering Curriculum," Journal of Engineering Education, 84 (2), 137-150, April 1995.
9. Finelli, C.J., A. Klinger and D.D. Budny, "Strategies for Improving the Classroom Experience," Journal of Engineering Education, 90 (4), 491-497, October 2001.
10. Fraser, D.M., R. Pillay, L. Tjatindi, and J.M. Case, "Enhancing the Learning of fluid Mechanics using Computer Simulations," Journal of Engineering Education, Vol. 96, No. 4, 2007, pp. 381-388.
11. Wicker, R.B., and R. Quintana, "An Innovation-Based Fluid Mechanics Design and Fabrication Laboratory," Journal of Engineering Education, Vol. 89, No. 3, 2000, pp. 361-367.
12. Walters, K., and K. Walters, "Introducing Talented High School Students via a Fluid Mechanics Short Course," Proceedings of the 2010 American Society for Engineering Education Annual Conference & Exposition, 2010.
13. Loinger, D.J., and J.C. Hermanson, "Integrated Thermal-Fluid Experiments in WPI's Discovery Classroom," Journal of Engineering Education, 91 (2), 239-243, April 2002.
14. McCabe, W.L., J.C. Smith and P. Harriott, Unit Operations of Chemical Engineering, 7th edition, McGraw-Hill, New York, 2005.

15. Green, D.W. and R.H. Perry, editors, Perry's Chemical Engineering Handbook, 8th edition, McGraw-Hill, New York, 2008.
16. Reader-Harris, M., Orifice Plates and Venturi Tubes, Springer International, Switzerland, 2015.
17. Alastal, K.M. and E.M.Y. Mousa, Hydraulics Lab, Experiment 5: Flow Through Small Orifices, Islamic University-Gaza, http://site.iugaza.edu.ps/mymousa/files/Experiment-5.pdf, accessed July 2016.
18. Wilkes, J.O., S.G. Birmingham, B.J. Kirby, Comsol (Femlab), C.Y. Cheng. "Fluid Mechanics for Chemical Engineers", 2nd Ed., Pearson Education, Inc., Boston, 2006.
19. Calvert, J.B., Coefficient of Discharge, http://mysite.du.edu/~jcalvert/tech/fluids/orifice.htm, accessed July 2016.

W. Roy Penney

Dr. Penney currently serves as Professor Emeritus of Chemical Engineering at the University of Arkansas. His research interests include fluid mixing and process design, and he has been instrumental in introducing hands-on concepts into the undergraduate classroom. Professor Penney is a registered professional engineer in the state of Arkansas.

Shannon L. Servoss

Dr. Shannon Servoss currently serves as Associate Professor and the Ralph E. Martin Endowed Professor in Chemical Engineering at the University of Arkansas. Her research interests include the study of peptoid-based materials for biomedical and environmental applications. Professor Servoss has incorporated an active-learning environment into her teaching of first year lab, fluid mechanics, and colloid and interface sciences.

Christa N. Hestekin

Dr. Hestekin currently serves as Associate Professor and Graduate Coordinator in the Ralph E. Martin Department of Chemical Engineering. She is the holder of the Virginia and Ansel Condray Professorship in Chemical Engineering and serves as President of the AES Electrophoresis Society. Her research interests include electric-driven separations, protein aggregation, and the development of active learning modules for K-12 students.

Edgar C. Clausen

Dr. Clausen currently serves as Professor, Interim Department Head and the Ralph E. Martin Leadership Chair in Chemical Engineering at the University of Arkansas. His research interests include bioprocess engineering, the production of energy and chemicals from biomass and waste, and enhancement of the K-12 educational experience. Professor Clausen is a registered professional engineer in the state of Arkansas.