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September 28, 1985

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Dr. J. D. Seader
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Comment: Address of project supervisor

Dear Dr. Seader:

Comment: Salutation

On September 3, 1985, you asked the team of A. L. Hewitt, R. A. MacDonald, and me to experimentally measure orifice-meter coefficients for the flow of water through a square-edged, 0.299-inch orifice with corner taps, located in a Schedule 40 one-inch steel pipe. Our project is described in detail in the attached report entitled "Calibration of an Orifice Meter."

Comment: Assignment, date and team members, report title

For pipe Reynolds numbers ranging from approximately 5,000 to 16,000, our measured coefficients varied with pipe Reynolds numbers and ranged from 0.572 to 0.631. Compared to a literature correlation reported in an NACA memo, our values are 3 to 5 percent low for pipe Reynolds numbers less than 10,000 and 2 to 5 percent high for pipe Reynolds numbers greater than 10,000. The discrepancies are generally within the estimated uncertainties (95% confidence level). New and clean, square-edged orifices are considered accurate to within 1 to 2 percent. In our case, the orifice inlet edges may not have been as sharp as required and the flow may not have been fully developed prior to the orifice entrance.

Comment: One paragraph summary of the report, including principal quantitative findings

The deviations from expected results may be a consequence of inadequate compliance with the rather severe ASME (1971) standards. We recommend that the project be repeated in strict compliance with ASME standards.

Comment: Conclusions

Sincerely,

David F. Scott

Comment: Signature and typed name

CALIBRATION OF AN ORIFICE METER

Comment: Title

by

David F. Scott

Comment: Author

Project No. 9F

Comment: Project number

Special Topics

Comment: Project category

Assigned: September 30, 1985

Due: October 28, 1985

Submitted: October 28, 1985

Project Team Members for Group F:

Comment: Team members and group leader

Andrew L. Hewitt, Group Leader

Robin A. MacDonald

David F. Scott

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David F. Scott

SUMMARY

Comment: Header repeats much of the information on the title page

Calibration of an Orifice Meter, Project 9F

Group F:

D. F. Scott (report author), A. L. Hewitt, R. A. MacDonald

Report Date: October 28, 1985

Coefficients for a square-edged, 0.299-inch diameter orifice meter with corner taps were determined experimentally for the horizontal flow of water in a Schedule-40 one-inch steel pipe over a range of pipe Reynolds numbers of approximately 5,000 to 16,000. Compared to a literature correlation, our measured coefficients, ranging from 0.572 to 0.631, are 3 to 5 percent low for pipe Reynolds numbers below 13,000 and 2 to 5 percent high for higher pipe Reynolds numbers. The discrepancies can be explained by the uncertainties in experimental measurements. In addition, the flow may not have been fully developed prior to the orifice and the orifice may not have had a sufficiently sharp, 90° entrance.

Comment: What

Comment: Findings

Comment: Conclusions

It is recommended that the project be repeated with a square edge orifice with flange taps that are designed and located according to ASME standards. We also recommend a sufficient length of pipe upstream of the orifice to insure fully developed flow prior to the orifice.

Comment: Recommendations

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I. INTRODUCTION

Comment: Background

According to de Nevers (1970), the orifice meter is used widely as a device for measuring the flow rate of a fluid in a pipeline. Compared with other head meters, such as the venturi meter and the nozzle, the orifice meter is less expensive to fabricate and install; however, the permanent energy loss is relatively high.

According to Sakiadis (1984), the orifice plate can have a square edged or sharp-edged hole. For measurement of the pressure drop across the orifice, the pressure taps can be at corner, radius, pipe, flange, or vena contracta locations. The direction of flow through the orifice can be horizontal, vertical, or inclined. The measured pressure drop across the orifice is related to the flow rate by means of an orifice coefficient, which accounts for friction, as defined in the next section of this report. Extensive research on and development of orifice meters has resulted in a standard orifice-meter design and standard correlations for the orifice coefficient, as reported in a booklet by the ASME Research Committee on Fluid Meters (1971). By proper application of the ASME standards, flow rates can be determined reproducibly to within 1 to 2 percent from measurements of orifice-meter pressure drop.

Comment: Key literature and reference to same

Nevertheless, it is common practice to calibrate an orifice meter before it is actually used in research, development, or production. The purpose of this project was to calibrate a sharp-edged orifice meter provided with corner taps for water flow in a Schedule 40 one-inch steel pipe and to compare the measured orifice coefficients with literature values. A calibrated rotameter was used to measure the actual water flow rate, which was varied over more than a three-fold range.

Comment: Reference to problem statement

Comment: Short description of procedures

II. THEORY

The theory for flow through an orifice meter is presented in several textbooks and handbooks. The following development is similar to the treatment given by de Nevers (1970).

Comment: Literature reference

An orifice meter of the type used in this project is shown schematically in Fig. 1. If steady-state, incompressible, frictionless, steady flow is assumed between Station 1, located upstream from

the orifice plate, and Station 2, located at the plane of the orifice hole, application of the Bernoulli equation for horizontal flow gives

$$\frac{P_1}{\rho} + \frac{V_1^2}{2g_c} = \frac{P_2}{\rho} + \frac{V_2^2}{2g_c} \quad (1)$$

Comment: Theory is developed from fundamentals. Equations are numbered and the numbers are shown at the right margin.

All symbols are defined in the Nomenclature table at the end of the text. The equation of continuity for steady-state, incompressible flow relates V_1 to V_2 as follows:

$$V_1 A_1 = V_2 A_2 \quad (2)$$

Comment: Symbols are defined by reference to the table of nomenclature.

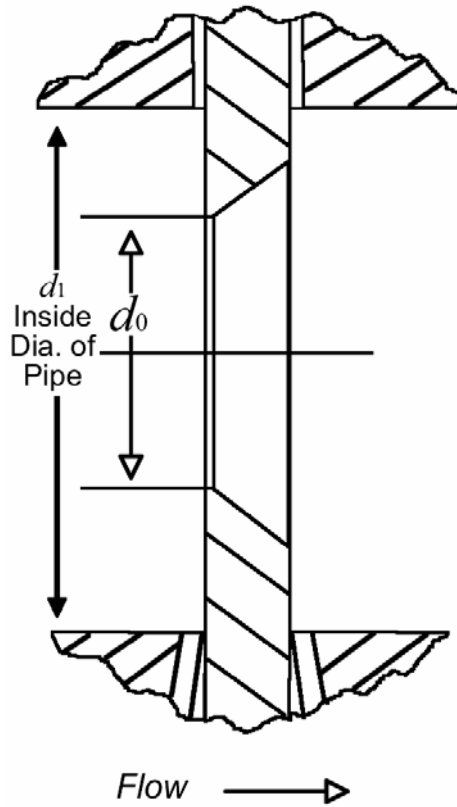
Solving Equation (2) for V_1 , substituting the result into Equation (1), and solving for V_2 yields

$$V_2 = \left[\frac{2g_c(P_1 - P_2)}{\rho \left(1 - \frac{A_2^2}{A_1^2} \right)} \right]^{1/2} \quad (3)$$

Comment: Equations are created in Microsoft Equation Editor.

In reality, the pressure, P_2 , is not measured at the orifice hole but at some downstream position, P_2' . Furthermore, frictional losses for the flow between the pressure taps occur due to turbulence. In practice, these effects are accounted for by the introduction of an orifice coefficient, C_d , into Equation (3) to give

$$V_2 = C_d \left[\frac{2g_c(P_1 - P_2')}{\rho \left(1 - \frac{A_2^2}{A_1^2} \right)} \right]^{1/2} \quad (4)$$



Comment: This figure was prepared by scanning the original.

Figure 1 Sharp-edged orifice meter with corner taps, copied from Crane (1957).

Finally, it is common to incorporate the area-ratio factor into a modified orifice coefficient, C , defined as

$$C = \frac{C_d}{\left(1 - \frac{A_2^2}{A_1^2}\right)^{1/2}} \quad (5)$$

Equation (4) is then simplified to

$$V_1 = C \left[\frac{2g(-\Delta P)}{\rho} \right]^{1/2} \quad (6)$$

where $(-\Delta P) = P_1 - P_2'$.

More conveniently, Equation (6) may be written in terms of the mass-flow rate where

$$\dot{m} = V_2 A_2 \rho \quad (7)$$

Substitution of Equation (7) into Equation (6) produces

$$\dot{m} = C A_2 [2 \rho g_c (-\Delta P)]^{1/2} \quad (8)$$

Alternatively, for an incompressible fluid, a volumetric-flow form of Equation (8) can be derived. Since

$$Q = V_2 A_2 \quad (9)$$

Equation (6) may be written as

$$Q = C A_2 \left(\frac{2g_c(-\Delta P)}{\rho} \right)^{1/2} \quad (10)$$

Comment: We finally arrive at the working equation.

Equation (10) was used to compute the orifice coefficient C from experimental data.

As discussed in detail by the ASME Research Committee on Fluid Meters (1971), the orifice coefficient, C, depends mainly on the type of orifice hole, the area ratio, A_2/A_1 , the location of the pressure taps, and the pipe Reynolds number given by

$$N_{Re_1} = \frac{D_1 V_1 \rho}{\mu} \quad (11)$$

Alternatively, the Reynolds number can be written in terms of the volumetric flow rate as

$$N_{Re_1} = \frac{4Q\rho}{\pi D_1 \mu} \quad (12)$$

In this study, a square-edged orifice meter with corner taps was used. This type of orifice meter is mentioned but not discussed in detail in the ASME (1971) work. It is considered in NACA TM 952 (1940), which presents the orifice coefficient correlation redrawn in Crane T.P. 410 (1957) and shown in Figure 2. As would be expected from friction considerations, the orifice coefficient is seen to decrease with decreasing ratio of orifice diameter to pipe diameter. However, in no case is the orifice coefficient less than 0.59. Above a pipe Reynolds number of 200,000, depending on the ratio D_2/D_1 , the orifice coefficient is independent of Reynolds number. The experimentally derived values of C from this study were compared with the correlation of Figure 2.

Comment: Comparison with correlation from the literature.

It should be noted that the use of the orifice discharge coefficient, C_d , is more common than the use of the orifice coefficient, C , because the value of C_d asymptotically approaches a constant value of approximately 0.61 at high values of the pipe Reynolds numbers. The orifice coefficient, C , was used in this study so as to be consistent with the literature correlation of Fig.2.

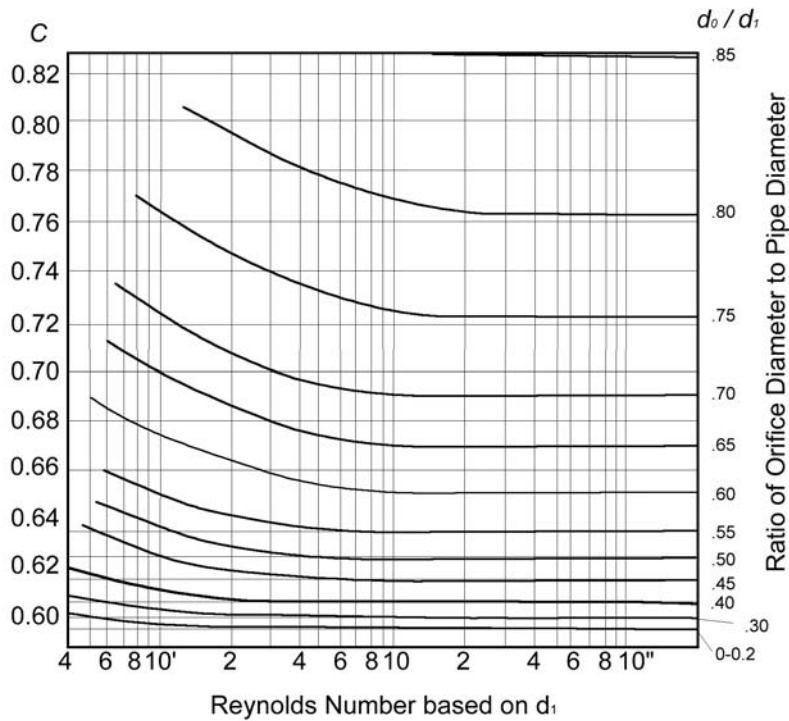


Figure 2 Orifice coefficient, C , for a sharp-edged orifice meter with corner taps. Copied from Crane (1957). Here d_0 is the orifice diameter and d_1 is the pipe diameter.

III. APPARATUS AND PROCEDURE

The experimental apparatus was assembled on a tabletop the Chemical Engineering Laboratory, located in Room 3290 of the Merrill Engineering Building. A schematic drawing of the assembled equipment is shown in Figure 3, with a detailed schematic drawing of the orifice meter and manometer given in Figure 4. Distilled water at ambient temperature entered the flow system through a full-open gate valve from a constant-head tank, located on the floor above. The flow rate of the water was controlled by a globe valve and measured by a calibrated rotameter before passing through the orifice meter connected to a manometer to measure the pressure drop. The water was discharged to a floor drain. The flow system used one-inch

Comment: Figure 3 refers to schematic of equipment

Comment: Figure 4 refers to mechanical drawing of apparatus

Schedule 40 steel pipe throughout and was designed to operate in a continuous, steady-state, steady-flow mode.

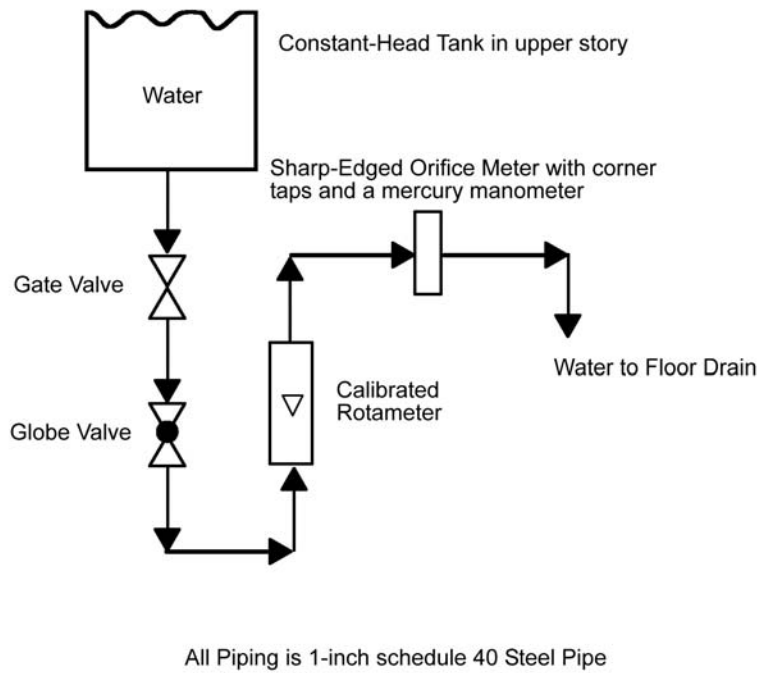
Detailed specifications and dimensions of the major items of equipment in the flow system are listed in Table E-1 in Appendix E. The rotameter was rated for a nominal full-scale flow capacity of 20 gpm of water at 20°C. The manufacturer's calibration curve is included as Fig. C-1 in Appendix C and was not verified in this study. The diameter of the orifice as measured with inside calipers and a micrometer was 0.299 inches, giving an orifice-diameter-to-inside-pipe diameter ratio, D_o/D_p , of 0.285.

Comment: Detailed specifications

The operating procedure included the following steps.

Comment: Operating procedure

1. The constant-head water tank was checked to be sure it was functioning properly.
2. The manometer was checked for the absence of air bubbles in the water legs above the mercury and for identical levels for H_1 and H_2 .
3. The globe valve was closed.
4. The gate valve was fully opened.
5. The globe valve was slowly opened until a desire and steady reading on the rotameter was observed.
6. The mercury levels in the manometer were observed. If oscillation was occurring, the manometer valves were used to dampen the oscillations so as to obtain constant mercury levels.
7. The following readings were taken:
 - a) Location of the bob float in the rotameter. The float was read at the location shown by the arrow in Fig. D-1.
 - b) Location of the mercury-water interface levels on both sides of the manometer. The tops of the meniscuses were read.
 - c) Temperature of the water in the constant-head tank using a mercury-in-glass thermometer.
8. Steps 4 through 6 were repeated for a new rotameter setting.

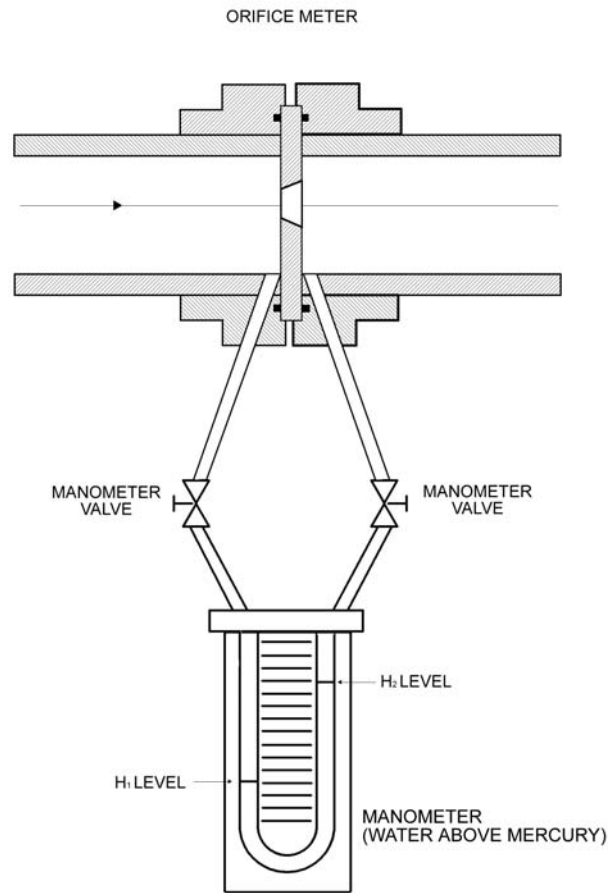


Comment: This is a flow diagram. It shows the functional relationships and flow directions for the important pieces of equipment. It is not intended to be a picture of the apparatus. A photograph can be included in addition to the flow diagram if it is needed. Flow diagrams are generally more informative than photographs.

Figure 3 Flow diagram of experimental system.

The density and viscosity of water over a small ambient-temperature range were required for correlating the data. Based on data in Liley, Reid and Buck (1984), the density of water was taken to be constant at 62.3 lb/ft^3 , and the viscosity of water was estimated by use of the chart on page 3-252 of this reference.

Comment: Physical properties



Comment: This is a mechanical drawing that shows, more or less to scale, the physical relationships of the parts of the orifice meter-manometer system.

Figure 4 Schematic of orifice meter and manometer.

IV. RESULTS AND DISCUSSION OF RESULTS

The experimental raw data are listed in Table A-1 of Appendix A. Six runs were made, each at a different flow rate. As shown, the rotameter reading varied over a 3.6 fold range from 7.5 percent to a maximum of 28.5 percent of full scale, corresponding to a water flow rate range of approximately 1.6 to 5.7 gpm. The water temperature varied from 17.5 to 22°C.

Comment: Raw data

The manometer readings H_2 and H_1 , shown in Figure 4, were converted to pressure drop by the following equation based on the principles of fluid statics:

$$(-\Delta P) = (H_2 - H_1)(\rho_{Hg} - \rho_{H_2O}) \left(\frac{g}{g_c} \right) \quad (13)$$

The rotameter readings were converted to volumetric flow rates with the calibration curve given in Appendix D. The orifice area, A_2 , was computed from the orifice diameter, D_2 , to be 0.0702 in² or 0.000488 ft². The orifice coefficient and accompanying Reynolds number were computed for each run from Equations (10) and (12), respectively. Sample calculations are given in Appendix B.

The calculated results for all six runs are listed in Table 1 and plotted in Figure 5, where it is seen that the orifice coefficients varied in a random fashion from 0.572 to 0.631 for a 3.4-fold pipe-Reynolds-number range of from almost 5,000 to more than 16,000. Included in Figure 5 is a literature curve from the previously mentioned NACA (1940) report showing an almost constant value of 0.60 for the orifice coefficient. In general, our experimental data straddle the literature curve with data below the curve for pipe Reynolds numbers in the transition region ($2,100 < N_{Re} < 10,000$) and data above the curve for turbulent-flow Reynolds numbers. In this latter region, our average measured orifice coefficient is 0.623, which is almost 4 percent higher than the literature value. In the transition region, our measured coefficients are from 3 to 5 percent lower than the literature values.

Comment: Calculated results

According to Sakiadis (1984), a new and clean square-edged orifice is considered to be accurate to within 1 to 2 percent when used with published correlations for the orifice coefficient. Our experimental data were not within that range of accuracy. There are several possible reasons for lack of accuracy:

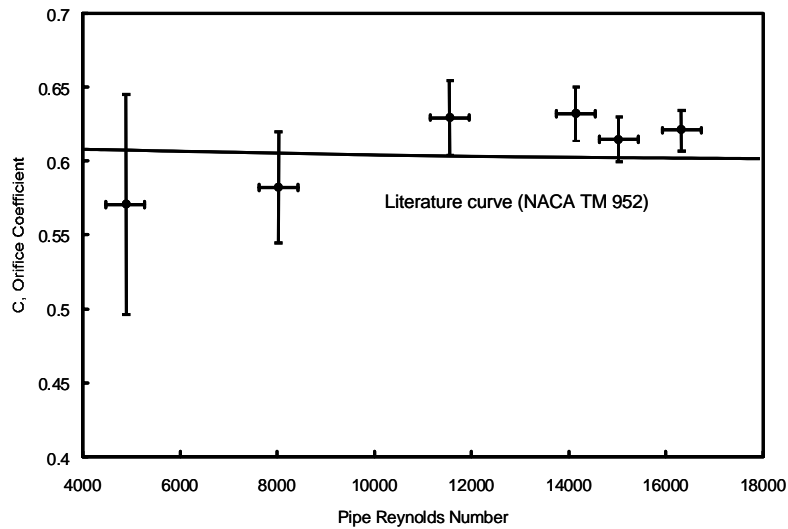
Comment: Accuracy

1. The use of a sharp-edged (conical-edge) orifice. According to ASME (1971), research on square-edged orifices has shown that measured coefficients are subject to installation and inlet conditions. This may be particularly true for the transition region of flow, where our first two runs were made. The ASME does not recommend sharp-edged orifices.

Table 1
Calculated results.

Run	Flow Rate, Q, ft ³ /s	Orifice Temp., °F	Orifice (-ΔP), lbf/ft ²	Orifice Coefficient	Pipe Reynolds Number
1	0.00343	71.6	146	0.57	4,900
2	0.00571	70.7	391	0.58	8,000
3	0.00822	70.7	694	0.63	11,600
4	0.01050	68.0	1,124	0.63	14,200
5	0.01164	65.3	1460	0.61	15,000
6	0.01301	63.5	1790	0.62	16,300

Comment: A simple table presents the experimental findings in a compact form. More detailed tables appear in the appendices, as needed.



Comment: This figure was prepared in Excel and modified in PowerPoint.

Figure 5 Comparison of measured orifice coefficients to reported values. The indicated uncertainties are at the 95 % confidence level and are summarized in Table E-1.

2. The use of corner taps. Although no reason is given, ASME (1971) omits any recommendation or correlation for orifice meters with corner taps.
3. Lack of sufficient length of straight pipe upstream of the orifice plate, particularly for runs where the pipe Reynolds number was in the transition region. For accuracy and reproducibility, the flow should be fully developed before reaching the orifice. In our apparatus, only 10 diameters of straight pipe were provided upstream of the orifice. ASME (1971) recommends 13 diameters for our piping configuration.
4. Location of the globe valve used to control the flow rate of water. For the location shown in Figure 3, the pressure drop across the valve could have caused a release of dissolved air in the form of bubbles downstream of the valve. The presence of bubbles in the water flowing through the rotameter could have caused an error in the flow rate measurement; however, the presence of bubbles was not observed.
5. Uncertainties in measurements (95% confidence level). Assuming that the calibration curve for the rotameter and the physical properties of the fluids were known with certainty, the uncertainties, with a 95% confidence level, were estimated to be as follows:
 - a) Rotameter reading, ± 0.5 (for a scale of 0 to 100)
 - b) Manometer levels, ± 0.05 inch
 - c) Thermometer reading, $\pm 0.25^\circ\text{C}$
 - d) Orifice diameter, ± 0.001 inches.

Comment: Uncertainties should always be given with the specified confidence level.

In addition, based on information in Sakiadis (1984), it was assumed that the uncertainty in the standard inside-pipe diameter of 1.049 inches was ± 0.02 inches.

The propagation of the above uncertainties into the equations used to process the data is presented in detail in Appendix F. The resulting uncertainty in the calculated orifice coefficients ranges from ± 0.07 at the lowest N_{Re1} down to ± 0.01 at the highest N_{Re1} . The corresponding uncertainty in N_{Re1} ranges from ± 340 to ± 440 . The uncertainty in β , the ratio of orifice diameter to pipe inside diameter, is ± 0.006 .

The uncertainties are depicted in Figure 5 by including horizontal and vertical extensions on the six experimental data points. Figure 5 shows that, after the uncertainties are taken into account, the experimental data are generally in agreement with the literature correlation.

V. CONCLUSIONS AND RECOMMENDATIONS

Orifice coefficients were determined experimentally for the flow of water at pipe Reynolds numbers from approximately 5,000 to 16,000 through a sharp-edged, 0.299-inch diameter orifice installed in a Schedule 40 one-inch steel pipe and provided with corner taps. The coefficients varied irregularly with pipe Reynolds number from a low of 0.57 in the transition region to a high of 0.63 under turbulent-flow conditions.

Comment: Conclusions

Compared to a literature correlation, our orifice coefficients are 3 to 5 percent lower at pipe Reynolds numbers in the transition region below 10,000. For turbulent-flow Reynolds numbers, our coefficients are 2 to 5 percent higher than the literature correlation. Thus, our values are not within the 1 to 2 percent deviation range claimed by ASME (1971) for a well-designed orifice meter. The discrepancies were explained by experimental uncertainties, based on our best judgment of the uncertainty for each of our measurements.

An additional explanation for the deviation of our results is the unreliability of a square-edged orifice with corner taps, particularly when it is operated in the transition region without a suitable inlet length that will guarantee that fully developed flow occurs before the flow reaches the orifice plate.

It is recommended that a carefully machined square-edged orifice plate, between flanges with carefully machined flange taps, be installed, following the recommendations of the ASME Research Committee on Fluid Meters (1971). Extensive studies show that this type of orifice meter gives results that are reproducible to within 1 to 2 percent. Furthermore, it is recommended that the location of the globe valve be changed from upstream to downstream of the rotameter and that the inlet length of straight pipe just upstream of the orifice meter be increased to at least 13 pipe diameters.

Comment: Recommendations

NOMENCLATURE

Comment: Every symbol that appears in the text must appear in this table and be defined. The dimension of each must be given. If a quantity is dimensionless, a hyphen is used to so indicate.

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
A_1	Inside cross sectional area for the pipe	ft ²
A_2	Cross sectional area for the orifice hole	ft ²
C	Orifice coefficient	-
C_d	Orifice discharge coefficient	-
D_p	Inside pipe diameter	ft
D_o	Orifice hole diameter	ft
g	Acceleration due to gravity	ft/s ²
g_c	Universal constant, 32.2	lb-s ² /lbf-ft
H_1	Lower manometer-fluid level	ft
H_2	Higher manometer-fluid level	ft
\dot{m}	Mass flow rate	lb/s
N_{Re1}	Pipe Reynolds number	-
P_1	Pressure in pipe upstream of orifice	lbf/ft ²
P_2	Pressure at plane of orifice hole	lbf/ft ²
P_2'	Pressure in pipe downstream of orifice	lbf/ft ²
Q	Volumetric flow rate	ft ³ /s
RR	Rotameter reading	% of full scale
T	Temperature	°C or °F
V_1	Fluid velocity in pipe	ft/s
V_2	Fluid velocity in orifice hole	ft/s
<u>Greek</u>		
β	Ratio of orifice-hole diameter to pipe ID	-
$-\Delta P$	Pressure drop across the orifice, $P_1 - P_2'$	lbf/ft ²
λ_i	Uncertainty in measurement	(depends on i)

ρ	Fluid density	lb/ft ³
μ	Fluid viscosity	lb/ft-s

REFERENCES

Comment: Every document referred to in the text is listed in the References. The style chosen here lists them alphabetically.

ASME, *Fluid Meters: Their Theory and Application*", Sixth Ed., Bean, H. S. Ed., ASME Research Committee on Fluid Meters, New York, NY, p 58-60, 73, 179-208, 211-215, (1971)

Crane, "Flow of Fluids Through Valves and Fittings," *Crane Technical Paper 410*, Crane Company, Chicago, Ill. p A19, (1957)

de Nevers, N., *Fluid Mechanics*, Addison-Wesley, Reading, MA , p 131, 139, and 144, (1970)

Liley, P.E., R.C. Reid and Evan Buck, "Physical and Chemical Data", in *Perry's Chemical Engineers' Handbook*, Sixth Ed., D. Green and J. O. Maloney, Eds., McGraw-Hill, New York, NY, p 3-75, (1984)

NACA, "Standards for Discharge Measurement With Standardized Nozzles and Orifices", *NACA Technical Memorandum 952*, NASA, Washington, D.C., p 4, 24; Data sheet 1; Figure IV, (Sept. 1940).

Sakiadis, B.C., "Fluid and Particle Mechanics", in *Perry's, op cit.*" p 3-251, 5-14 to 5-16 and 6-42. (1984).

Silcox, G. D., "Basic Analysis of Data," unpublished printed notes, Univ. of Utah, Salt Lake City, Utah (1999).

APPENDICES
APPENDIX A
RAW DATA

Table A-1
Raw experimental data obtained October 16, 1985.

Run	Rotameter Reading, % Full Scale	Manometer Height, H ₂ , inches	Manometer Height, H ₁ , inches	Water Temp., °C
1	7.5	1.30	-0.95	22.0
2	12.5	3.20	-2.80	21.5
3	18.0	5.55	-5.10	21.5
4	23.0	8.85	-8.40	20.0
5	25.5	11.40	-11.00	18.5
6	28.5	13.95	-13.50	17.5

APPENDIX B
SAMPLE CALCULATIONS

Comment: Detailed sample calculations with all data sources.

The following sample calculations use the raw data from Run 1 of Table A-1 in Appendix A.

Constants

$$\rho_{\text{Hg}} = (13.55)(62.3) = 844.2 \text{ lb/ft}^3$$

$$\rho_{\text{H}_2\text{O}} = 62.3 \text{ lb/ft}^3$$

$$g = 32.2 \text{ ft/s}^2$$

$$g_c = 32.2 \text{ lb-s}^2/\text{lbf-ft}$$

$$D_1 = \text{inside pipe diameter} = 1.049 \text{ in} = 0.0874 \text{ ft}$$

$$D_2 = \text{orifice diameter} = 0.299 \text{ in} = 0.0249 \text{ ft}$$

$$A_2 = \text{orifice cross sectional area} = 0.0702 \text{ in}^2 = 0.000488 \text{ ft}^2$$

$$\beta = D_2/D_1 = 0.285$$

Run data

Rotameter reading = 7.5 % of full scale

$$H_2 = 1.30 \text{ in} = 0.108 \text{ ft}$$

$$H_1 = -0.95 \text{ in} = -0.079 \text{ ft}$$

$$T = 22.0^\circ\text{C} = 71.6^\circ\text{F}$$

Calculation of Flow Rate

Comment: Explanation of how the calculation is made. This should be similar in style and detail to what appears in most textbooks.

From Appendix C, the correlating equation for the manufacturer's rotameter calibration is

$$RR = 0.0775 Q \quad (\text{B-1})$$

where RR = rotameter reading, % of full scale, Q is the Volumetric flow rate of water at 20°C in cm³/s. If the effects of water temperatures in the range of 17.5 to 22°C are neglected, the rotameter calibration equation for flow rates in ft³/s becomes

$$Q = \frac{RR}{2190} \quad (\text{B-2})$$

where Q is in ft³/s. Then

$$Q = \frac{7.5}{2190} = 0.00343 \frac{\text{ft}}{\text{s}}$$

Calculation of (-ΔP)

From Equation (13),

$$\begin{aligned} (-\Delta P) &= (H_2 - H_1)(\rho_{Hg} - \rho_{H_2O}) \left(\frac{g}{g_c} \right) \\ &= [0.108 - (-0.079)] [844.2 - 62.3] \left(\frac{32.2}{32.2} \right) \\ &= 146 \text{ lbf / ft}^2 \end{aligned}$$

Calculation of Orifice Coefficient

From Equation (10),

$$Q = CA_2 \left(\frac{2g_c(-\Delta P)}{\rho} \right)^{1/2}$$

and

$$\begin{aligned} C &= \frac{Q}{A_2 \left(\frac{2g_c(-\Delta P)}{\rho} \right)^{1/2}} \quad (\text{B-3}) \\ &= \frac{0.00343}{0.000488 \left(\frac{2(32.2)(146)}{62.3} \right)^{1/2}} \\ &= 0.572 \end{aligned}$$

Calculation of the Pipe Reynolds Number

We used linear interpolation for the water-viscosity data in the section "Apparatus and Procedure."

Viscosity of water at 71.6°F =

$$\begin{aligned}
 &= 0.978 - (0.978 - 0.953) \left(\frac{71.6 - 70}{72 - 70} \right) \\
 &= 0.958 \text{ cp} = 0.000644 \frac{\text{lb}}{\text{ft} \cdot \text{s}}
 \end{aligned}$$

From Equation (12)

$$\begin{aligned}
 N_{Re1} &= \frac{4Q\rho}{\pi D_1 \mu} \\
 &= \frac{(4)(0.00343)(62.3)}{(3.14)(0.0874)(0.000644)} \\
 &= 4840
 \end{aligned}$$

The above-calculated results for Run 1 are listed in Table 1.

APPENDIX C
ROTAMETER CALIBRATION

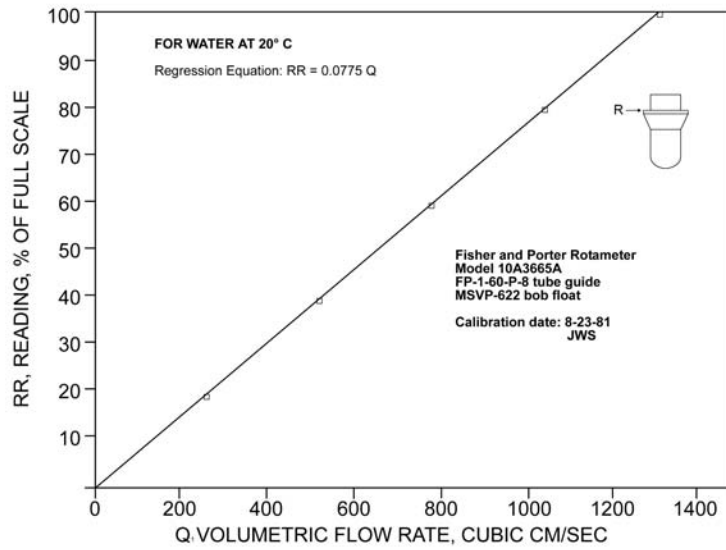


Figure C-1 Rotameter calibration curve, copied from the report of JWS.

Comment: Note that the author is using a calibration prepared by JWS (a student from the previous year) without giving a reference in the Reference Section. This is unacceptable.

APPENDIX D
MAJOR ITEMS OF EQUIPMENT

Table D-1
Specifications and dimensions of major items of equipment.

1. Rotameter:

Fisher and Porter Company, Model 10A3665A with FP-1-60-P-8 tube guide and NSVP-622 bob float. Manufacturer's calibration curve is given in Fig. C-1 of Appendix C.

2. Orifice Meter and Piping:

Sharp-edged orifice with corner taps located in one-inch Schedule 40 steel pipe.

Measured orifice diameter = $D_2 = 0.299$ in.

Inside pipe diameter $D_1 = 1.049$ in.

(from page 6-42 of Sakiadis (1984)).

$D_2/D_1 = 0.285$

Length of orifice cylindrical section: 0.02 inches

Angle of chamfer: 45°

Length of pipe between ell and orifice plate: 10.5 inches.

3. Manometer:

Dwyer model 36-W/M glass, U-tube manometer, with valves to dampen oscillation, and using mercury (s.g. = 13.55) as the manometer fluid.

APPENDIX E
UNCERTAINTY ANALYSIS

The following uncertainties (95% confidence level) were estimated for the experimental measurements:

Comment: The uncertainty analysis has no meaning unless the confidence level is specified.

$$\lambda_{RR} = \pm 0.5$$

$$\lambda_{H1} = \lambda_{H2} = 0.05 \text{ in.} = 0.00417 \text{ ft}$$

$$\lambda_T = \pm 0.25^\circ\text{C}$$

$$\lambda_{D1} = \pm 0.02 \text{ in.} = \pm 0.00167 \text{ ft}$$

$$\lambda_{D2} = \pm 0.001 \text{ in.} = \pm 0.0000833 \text{ ft}$$

Uncertainty in the Orifice Coefficient:

Combining Equations B-2, 13, and B-3 with the relation, $A_2 = \pi D_2^2/4$, gives

$$C = \frac{RR}{2190 \frac{\pi D_2^2}{4} \left[\frac{2(H_2 - H_1)(\rho_{Hg} - \rho_{H2O})g}{\rho_{H2O}} \right]^{0.5}} \quad (\text{E-1})$$

or

$$C = \frac{RR}{48900 D_2^2 (H_2 - H_1)^{0.5}} \quad (\text{E-2})$$

The uncertainties were propagated using a spreadsheet and the procedure discussed by Silcox (1999). The results are summarized in Table E-1.

Uncertainty in the Pipe Reynolds Number

Combining Equations B-2 and 12, and using a polynomial to represent the viscosity of water as a function of temperature, give the Reynolds number:

$$N_{Re} = \frac{RR}{27.61D_1(3.664 \times 10^{-7} * T^2 - 3.371 \times 10^{-5} * T + 1.201 \times 10^{-3})} \quad (E-3)$$

The uncertainties were propagated using a spreadsheet and the procedure discussed by Silcox (1999). The results are summarized in Table E-1.

Uncertainty in D_2/D_1 ratio

The ratio of diameters is

$$\beta = \frac{D_2}{D_1} \quad (E-4)$$

The uncertainties were propagated using a spreadsheet and the procedure discussed by Silcox (1999). The results are summarized in Table E-1.

Summary of Estimates in Uncertainty for All Six Runs

The estimated uncertainties are given in Table E-1. These uncertainties were incorporated in Figure 5.

Table E-1

Uncertainties in calculated results (95% confidence level).

Run	λ_C	λ_{NRe}
		1
1	± 0.07	± 340
2	± 0.04	± 360
3	± 0.03	± 400
4	± 0.02	± 420
5	± 0.02	± 430
6	± 0.01	± 440
	$\lambda_\beta = \pm 0.006$	