ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

PRODUCTION NOTE

University of Illinois at Urbana-Champaign Library
THE ORIFICE AS A MEANS OF MEASURING FLOW OF WATER THROUGH A PIPE

BY
RAYMOND E. DAVIS
AND
HARVEY H. JORDAN

BULLETIN No. 109
ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

PRICE: TWENTY-FIVE CENTS
EUROPEAN AGENT
CHAPMAN & HALL, LTD., LONDON
THE Engineering Experiment Station was established by act of the Board of Trustees, December 8, 1903. It is the purpose of the Station to carry on investigations along various lines of engineering and to study problems of importance to professional engineers and to the manufacturing, railway, mining, constructional, and industrial interests of the State.

The control of the Engineering Experiment Station is vested in the heads of the several departments of the College of Engineering. These constitute the Station Staff and, with the Director, determine the character of the investigations to be undertaken. The work is carried on under the supervision of the Staff, sometimes by research fellows as graduate work, sometimes by members of the instructional staff of the College of Engineering, but more frequently by investigators belonging to the Station corps.

The results of these investigations are published in the form of bulletins, which record mostly the experiments of the Station’s own staff of investigators. There will also be issued from time to time, in the form of circulars, compilations giving the results of the experiments of engineers, industrial works, technical institutions, and governmental testing departments.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University of Illinois: either above the title or below the seal is given the number of the Engineering Experiment Station bulletin or circular which should be used in referring to these publications.

For copies of bulletins, circulars, or other information address the

ENGINEERING EXPERIMENT STATION,
URBANA, ILLINOIS.
UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 109 DECEMBER, 1918

THE ORIFICE AS A MEANS OF MEASURING FLOW OF WATER THROUGH A PIPE

BY

RAYMOND E. DAVIS
ASSOCIATE IN CIVIL ENGINEERING

AND

HARVEY H. JORDAN
ASSISTANT PROFESSOR IN GENERAL ENGINEERING DRAWING

ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA
This page is intentionally blank.
CONTENTS

I. INTRODUCTION

1. Scope of Bulletin ................................................................. 7
2. Other Experiments ................................................................. 8
3. Acknowledgment ...................................................................... 8
4. Notation .................................................................................. 9

II. ANALYTICAL RELATION BETWEEN VELOCITY, DROP IN PRESSURE HEAD, AND LOST HEAD

5. Relation between Drop in Pressure Head and Velocity of Flow ......... 11
6. Expression for Lost Head .......................................................... 12

III. TESTS AND RESULTS

7. Scope of Experiments ............................................................... 14
8. Apparatus .............................................................................. 16
9. Water Supply and Measurement ............................................... 16
10. Pressure Changes near Orifice .................................................. 19
11. Deductions on Behavior of the Jet ............................................ 21
12. Relation between Drop in Pressure Head and Discharge ............... 22
13. Simplified Equations for Velocity and Discharge ........................ 31
14. Application to Other Sizes of Pipes .......................................... 34
15. Empirical Relation between Velocity and Drop in Pressure Head .... 35
16. Empirical Formula for Lost Head .............................................. 35
17. Choice of Orifice .................................................................... 36
18. Computations for Discharge ..................................................... 39
19. Errors and Precautions ............................................................ 40

IV. EFFECT OF DEVIATION FROM STANDARD CONDITIONS

20. General Remarks .................................................................... 43
21. Throttling .............................................................................. 43
CONTENTS (CONTINUED)

22. Position and Number of Gage Connections ........................................ 44
23. Eccentricity ..................................................................................... 45
24. Bevel-edged Orifices ......................................................................... 46

V. SUMMARY

25. General Applicability of Pipe Orifice Method ................................... 50
26. Conclusions ..................................................................................... 50
LIST OF FIGURES

NO. | PAGE
---|---
1. Behavior of Jet | 11
2. Apparatus for Observing Pressure Changes | 17
3. Pressure Variations near Orifice | 20
4. Pipe Connections near Orifice | 23
5. Differential Gages | 24
6. Experimental Discharge Curves—4-inch pipe. | 28
7. Experimental Discharge Curves—6-inch pipe. | 29
8. Experimental Discharge Curves—12-inch pipe. | 30
9. Coefficients of Discharge | 32
10. Diameter Factor | 34
11. Relation between Lost Head and Drop in Pressure Head | 37
12. Relation between Maximum Drop in Pressure and Size of Orifice. | 37
13. Emergency Differential Gage | 41
14. Coefficients of Discharge for Bevel-edged Orifices | 47

LIST OF TABLES

NO. | PAGE
---|---
1. Diameters of Orifices and Pipes | 14
2. Position of Sections at Pressure Connections | 19
3. Sample Data | 25—27
4. Coefficient of Discharge | 30
5. Velocity Modulus | 33
6. Approximate Values of Drop in Pressure and Lost Head. | 38
7. Coefficients of Discharge for Bevel-edged Orifices | 46
This page is intentionally blank.
THE ORIFICE AS A MEANS OF MEASURING FLOW OF WATER THROUGH A PIPE

I. INTRODUCTION

1. Scope of Bulletin.—In this bulletin are given the results of tests made to determine the practicability of measuring the flow of water by means of the thin-plate circular orifice inserted in a pipe, to determine the experimental coefficients for calculating the velocity of the flow in the pipe and the discharge, and to determine the conditions most favorable to the use of such an orifice as a flow measuring device. An orifice thus inserted causes an abrupt change in the conditions of flow as the stream approaches and passes through the orifice and this change in the conditions of flow is accompanied by a considerable change in pressure head which may be readily measured and which varies with the velocity of flow in the pipe. The orifice inserted in a pipe line is looked upon more especially as a temporary or field device for measuring the flow of water through a pipe, being inexpensive, simple to construct, light in weight, and easy to install. There may be opportunities for its use in permanent installations where a continuous record is not necessary, loss in head is not an important factor, and the expense of any one of the common flow meters is not justified. In flanged pipe systems the thin-plate orifice may be inserted at a joint with little or no disturbance of existing piping; and in long pipe lines the loss in head caused by the orifice will be inconsiderable as compared with other losses. It would seem that this device might well be utilized, for example, in testing the efficiency of certain forms of pumps, in measuring the performance of individual wells of water works systems, in determining the water consumption for individual purposes in mills and factories, in measuring the discharge through city mains, and in distributing water for irrigation purposes. In planning and conducting the tests the conditions under which the orifice would ordinarily be found useful have been borne in mind, and no attempt has been made to refine apparatus or methods of observing beyond what might be expected in practice.
Tests were made to determine: (1) the positions of two cross-sections of the pipe, one section upstream from the orifice, the other downstream from the orifice, at which pressure head may be measured and the drop in pressure from one section to the other may be most favorably determined, (2) the relation between this drop in pressure head and the rate of discharge through the pipe, (3) the lost head occasioned by the orifice, (4) the effect of small deviations from what may be termed standard conditions, and (5) the proper size of orifice for given conditions. In the presentation of the results of these tests special attention has been given to the probable sources, magnitudes, and effects of the accidental and constant errors incidental to the observations. Attempt has been made through the use of tables and curves to render the results easily adaptable to all sizes of pipe from 4 inches to 20 inches in diameter and for all sizes of orifice up to five-sixths of the diameter of the pipe. In the belief that others than experienced hydraulicians may find use for the results, some attention has been given to matters connected with the construction, installation, and use of a form of apparatus adapted to normal practice.

2. Other Experiments.—The method of measuring water by inserting an orifice in the pipe line is not new. Partially closed valves have been calibrated as orifices for such use and experiments of a preliminary nature have been conducted recently with thin-plate orifices. In "Experiments on Water Flow through Pipe Orifices,"* Horace Judd reports the progress of somewhat similar experiments conducted at Ohio State University, the orifices being in plates of Monel metal 1/32 inch thick inserted in a 5-inch pipe.

In "Diaphragm Method of Measuring the Velocity of Fluid Flow in Pipes,"† Holbrook Gaskell, Jr., gives an account of a brief series of tests on 6-inch and 8-inch pipe.

3. Acknowledgment.—The tests were made in the Laboratory of Applied Mechanics of the University of Illinois in 1914-15 as graduate work in the Department of Theoretical and Applied Mechanics and in 1916-17 as an investigation of the University of Illinois Engineering Experiment Station. The investigations were under the general supervision of ARTHUR N. TALBOT, Professor of Municipal and Sanitary Engineering and in Charge of the Department of Theoretical and

*Jour. of the Am. Soc. of M. E., Sept. 1916.
Applied Mechanics. To Professor Talbot credit is due for valuable suggestions made during the preparation of this bulletin. To Professors M. L. Enger and Fred B. Seely, of the Department of Theoretical and Applied Mechanics, credit is due for many helpful suggestions made during the progress of the work.

The tests treated in this bulletin are the outgrowth of brief experiments by C. S. Mulvaney, of the class of 1914, conducted under the direction of V. R. Fleming, Assistant Professor of Applied Mechanics. The results of the experiments of Mr. Mulvaney were presented as an undergraduate thesis.

4. Notation.—Throughout the bulletin the following notation will be used:

\[ V = \text{mean velocity (ft. per sec.) in pipe at a section of normal uniform flow.} \]
\[ v = \text{velocity (ft. per sec.) of the jet issuing from the orifice at the section of greatest contraction.} \]
\[ A = \text{cross-sectional area of the pipe (sq. ft.).} \]
\[ Q = \text{rate of discharge (cu. ft. per sec.).} \]
\[ D = \text{diameter of the pipe (in.).} \]
\[ d = \text{diameter of the orifice (in.).} \]
\[ h_s = \text{lost head (ft. of water) caused by the orifice, including the loss due both to contraction and to sudden expansion of the jet.} \]
\[ h_b = \text{drop in pressure head (ft. of water); or change in pressure head as registered by a differential gage one column of which is connected to the pipe at a section of normal uniform flow upstream from the orifice and the other column of which is connected to the pipe in the same plane as the section of greatest contraction of the jet downstream from the orifice.} \]
\[ C = \text{coefficient of discharge.} \]
\[ C_c = \text{coefficient of contraction.} \]
\[ C_v = \text{coefficient of velocity.} \]
\[ g = \text{acceleration of gravity (ft. per sec.}^2). \]
\[ C_p = \text{factor depending on diameter of pipe.} \]
\[ K = \text{velocity modulus; or velocity corresponding to a drop in pressure head (}h_b\text{) of 1 ft.} \]
\( C_r \) = ratio factor, depending on \( \frac{D}{d} \).

\( F \) = factor showing the dependence of \( h_a \) on diameter of pipe.

\( J \) = coefficient expressing the relation between \( h_a \) and \( h_b \).

\( C' \) = coefficient of discharge for bevel-edged orifices.
II. ANALYTICAL RELATION BETWEEN VELOCITY, DROP IN PRESSURE HEAD, AND LOST HEAD

5. Relation between Drop in Pressure Head and Velocity of Flow.—In the use of the pipe orifice the velocity of flow in the pipe (or the rate of discharge) is calculated from the drop in the pressure head between a section upstream from the orifice and a section downstream from the orifice. It is desirable, therefore, to develop a simple rational expression for the velocity in terms of the drop in the pressure head. Furthermore, since the loss of head caused by the orifice in the pipe may be a determining factor in the selection of the proper orifice it is desirable that a rational expression be found for the lost head. Assumptions have been made concerning the behavior of the jet which have some experimental justification as will be discussed later.

Fig. 1. Behavior of Jet

Fig. 1 represents a longitudinal section of a pipe with the water passing through an orifice at $AA'$. Let section 1 be a section of normal uniform flow on the upstream side of the orifice. As the stream approaches the orifice from this section it converges and, if it may be
assumed to behave not unlike the jet issuing from the standard orifice in the open air, it continues to converge after leaving the orifice until the greatest contraction takes place at, let us say, section 2. The jet then expands until normal flow takes place at section 3.

Let \( h_1, h_2, \) and \( h_3 \) respectively be the pressure heads registered by piezometer tubes inserted at sections 1, 2, and 3, and let it be assumed that the pressure head \( h_2 \) is the same as it would be if the piezometer tube at section 2 were projecting through the wall of the pipe to the periphery of the jet at the contracted section.

Neglecting pipe friction, the drop in pressure head between the section of beginning of convergence and the section of greatest contraction (Fig. 1) is equal to the change in velocity head between the two sections plus the loss in head due to the contraction of the jet. Then by Bernoulli’s Law

\[
h_b = h_1 - h_2 = \frac{v^2}{2g} \frac{C_v^2}{C_e^2} - \frac{V^2}{2g}
\]

Since \( \frac{v}{V} = \frac{D^2}{C_e d^2} \) and \( C = C_e C_v \),

\[
j_v = \left[ \frac{(D/d)^4}{C_e} - 1 \right] \frac{v^2}{2g} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldottedexpectation
derivation of the expression in the preceding article it may be shown that
\[ h_a = h_1 - h_3 = \frac{V^2}{2g} \left[ \left( \frac{D}{d} \right)^4 \left( \frac{C^2}{C_e^2} - \frac{1}{C_e^2} \right) + \left( \frac{D}{d} \right)^2 \frac{1}{C_e} - 1 \right]^2 \).
\]

This is the loss of head caused by the orifice. It is evidently always less than the drop in pressure head of equation (1) but approaches that quantity as the ratio \( \frac{D}{d} \) increases.

In order properly to apply these equations, the sections previously referred to, particularly the section of beginning of convergence and the section of greatest contraction, must be studied experimentally. The method of modifying the rational equations to conform with the experimental results will be discussed later.
III. TESTS AND RESULTS

7. Scope of Experiments.—The principal tests were made on 4-inch, 6-inch and 12-inch pipe with eight sizes of orifices for each size of pipe as recorded in Table 1. It will be noted that the diameters of the orifices range from one-eighth to five-sixths the diameter of the pipe, and that the eight ratios of diameter of pipe to diameter of orifice for the 4-inch series are approximately the same as for the 6-inch and 12-inch series.

The mean velocity in the pipe ranged from 0.01 ft. per sec. with the smallest orifice of each series to a maximum velocity of about 23 ft. per sec. with the largest orifice of the 4-inch series, 14 ft. per sec. with the 6-inch series, and 3\(\frac{1}{4}\) ft. per sec. with the 12-inch series.

Experiments were conducted to investigate phases of the problem as follows:

(1) Pressure Variations and Behavior of Stream

By observations of pressure variations along the pipe the position of the following sections was found: (a) the section at which the flow in the pipe changes from normal uniform flow and the stream begins to converge towards the orifice; (b) the section at which the jet issuing from the orifice becomes fully expanded and normal uniform flow is resumed; and (c) the section of greatest contraction of

<table>
<thead>
<tr>
<th>4-inch Pipe (D=4.06) in.</th>
<th>6-inch Pipe (D=6.12) in.</th>
<th>12-inch Pipe (D=12.15) in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d)</td>
<td>(\frac{D}{d})</td>
<td>(d)</td>
</tr>
<tr>
<td>0.497</td>
<td>8.17</td>
<td>0.75</td>
</tr>
<tr>
<td>0.667</td>
<td>6.69</td>
<td>1.00</td>
</tr>
<tr>
<td>1.00</td>
<td>4.06</td>
<td>1.49</td>
</tr>
<tr>
<td>1.34</td>
<td>3.04</td>
<td>2.00</td>
</tr>
<tr>
<td>1.67</td>
<td>2.43</td>
<td>2.50</td>
</tr>
<tr>
<td>2.00</td>
<td>2.03</td>
<td>3.01</td>
</tr>
<tr>
<td>2.68</td>
<td>1.52</td>
<td>4.02</td>
</tr>
<tr>
<td>3.33</td>
<td>1.22</td>
<td>5.01</td>
</tr>
</tbody>
</table>
the jet issuing from the orifice. The change in pressure head was taken to indicate the change in area of stream flow, the section of greatest contraction being located where the pressure head is the least. The terms normal uniform flow, beginning of convergence, section of greatest contraction, and section where jet becomes fully expanded and normal uniform flow is resumed are used for convenience to describe the general phenomena at the several sections; they are not to be taken to define strictly the conditions of flow. The general behavior of the stream in the vicinity of the orifice was also studied.

(2) Relation between Drop in Pressure and Discharge

The observations of pressure variations along the pipe indicated that the two most favorable sections for gage connections, the sections giving the steadiest pressure and the most reliable drop in pressure head were a section at or slightly upstream from the section of beginning of convergence and one at the section of greatest contraction. For these sections a greater change in pressure head was found than for any other two sections in the vicinity of the orifice.

For measured rates of discharge the drop in pressure head as registered by a differential gage connected at approximately the section of beginning of convergence and at the section of greatest contraction was observed. From these tests coefficients of discharge will be derived.

(3) Lost Head

The lost head caused by the orifice, if pipe friction is disregarded, is represented by the change in pressure head between the section of beginning of convergence upstream from the orifice and the section of resumed normal uniform flow down stream from the orifice, or is the difference between the pressure heads at two sections of normal uniform flow, one section above and one below the orifice. Observations were made to determine the relation between lost head and discharge.

(4) Effect of Varying the Conditions

Tests were made to determine: (a) the effect of a small lateral displacement of the orifice, (b) the effect of throttling the gage on the precision of observations, (c) whether or not there is a measure
able difference between the drop in pressure head with gage connections made at the top of each section and the drop in pressure head with the gage connections made at the bottom of each section, (d) the effect of number of connections at each section on the precision of observations, and (e) the effect of beveling the upstream edge of the orifice.

The drop in pressure was measured between a section at approximately the beginning of convergence and the section of greatest contraction. The tests were made only on 4-inch and 6-inch pipe.

8. **Apparatus.**—The pipe upon which tests were made was commercial steel pipe which had been in service some years. In general there was a small but measurable difference between the diameters of the adjoining sections of pipe between which the orifice plate was inserted, and, due to roughnesses and other variations, the error of measuring the diameter was perhaps 0.02 inch. The pipe was horizontal and straight for a sufficient distance on each side of the orifice to make the effect from bends negligible.

All orifices were circular in shape and were cut in 3/16-inch steel plates. In general the edges of the orifices were square. To find the effect of a deviation from this standard, experiments were also made with bevel-edged orifices, a bevel of 45 degrees being made on the upstream side of the orifice in such a way as to leave a thickness of metal of 1/32 inch at the throat.

Drop in pressure head was measured by the usual form of U-tube differential gage, the water gage being used for small differences, and the mercury gage for large differences.

The gage connections to the pipe at the sections under consideration were ¼-inch pipe nipples. Care was taken that no burr was left at the inner edge of the tapped holes and that the nipples did not protrude beyond the inner surface of the pipe. The pipe nipples were connected with the gages by ordinary rubber tubing.

9. **Water Supply and Measurement.**—The supply of water was obtained from the 60-foot standpipe of the Hydraulic Laboratory. For most of the tests the water level in the standpipe was within a few feet of the top and a nearly constant head was maintained by a 2200-gallon duplex pump, the pump being automatically regulated. For most work the head remained nearly constant during a given run,
FIG. 2. APPARATUS FOR OBSERVING PRESSURE CHANGES
This page is intentionally blank.
but for large discharges surges occurred in the standpipe resulting in momentary fluctuations in pressure in the pipe.

When less than about 1/3 cu. ft. per sec., the discharge was measured by weight; when greater, by displacement.

Time of discharge was observed with a calibrated stop watch.

10. Pressure Changes near Orifice.—For these tests gage connections to the pipe were inserted at the sections indicated in Table 2,

<table>
<thead>
<tr>
<th>Diam. of Pipe</th>
<th>Sec. A to Orif.</th>
<th>Sec. B to Orif.</th>
<th>Orif. to Sec. C</th>
<th>Orif. to Sec. D</th>
<th>Orif. to Sec. E</th>
<th>Orif. to Sec. F</th>
<th>Orif. to Sec. G</th>
<th>Orif. to Sec. H</th>
<th>Orif. to Sec. I</th>
<th>Sec. A to Sec. I</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.12</td>
<td>4/4</td>
<td>2 1/4</td>
<td>5/4</td>
<td>2 3/4</td>
<td>8 1/4</td>
<td>20</td>
<td>38</td>
<td>74</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>12.15</td>
<td>5</td>
<td></td>
<td>4 3/4</td>
<td>16</td>
<td>40</td>
<td>76</td>
<td>127</td>
<td>132</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

section A being upstream from the orifice and the change in pressure head between adjacent sections was observed at from 20 to 40 rates of flow for each orifice. The maximum changes in pressure observed ranged from 0.01 ft. to 50 ft.

Fig. 2 shows the apparatus for observing changes in pressure head in the 12-inch pipe, the orifice plate being between the flanges near the left of the picture and the direction of flow being from left to right. At the sections adjacent to the orifice (section A and section D, Table 2), gage connections were inserted both in the top and in the bottom of the pipe, and the two nipples at each of these sections were brought to a union. Two connections were also used at section I. At other sections a single nipple was inserted in the bottom of the pipe.

The results of the observations are shown graphically in Fig. 3. For ease in making comparison, changes in pressure head along the pipe are shown in terms of the lost head caused by the orifice (ratio of change in pressure head to lost head), an allowance for pipe friction having been made.
For each $\frac{D}{d}$ the ordinate of the curve at any section was obtained by averaging the ratios for all rates of flow, there being nothing to indicate a consistent variation between these ratios at low rates of flow.
and at high rates of flow. That there are not three curves shown for each $\frac{D}{d}$ merely indicates that there is close agreement between the general behavior of the jet for one size of pipe and the general behavior for other sizes, and does not indicate that the size of pipe has no influence on the relation between velocity and change in pressure head. The dotted portion of the curve for $\frac{D}{d} = 1.22$ is regarded as uncertain.

11. Deductions on Behavior of the Jet.—A study of the observations of the changes in pressure head (which are too numerous to be shown here) and of the curves in Fig. 3 warrants the following deductions:

(1) The location of the section of beginning of convergence as the stream approaches the orifice is approximately 0.8 of the diameter of the pipe upstream from the plane of the orifice, for $\frac{D}{d} = 1.2$, and it gradually approaches the orifice as $\frac{D}{d}$ increases.

(2) The section of greatest contraction is at a fairly constant distance of 0.4 of the pipe diameter downstream from the plane of the orifice for values of $\frac{D}{d}$ of 1.5 or greater. As $\frac{D}{d}$ becomes less than 1.5, the section of greatest contraction gradually approaches the orifice.

(3) The distance from the orifice to the section at which the jet has fully expanded and normal uniform flow is resumed varies between 3 and 4 pipe diameters, increasing as $\frac{D}{d}$ decreases until $\frac{D}{d}$ becomes 1.5, and thereafter probably decreasing.

(4) Downstream from the contracted section there is a region of greatly disturbed pressure. As the diameter of the orifice approaches the diameter of the pipe, this region approaches the section of greatest contraction and the pressure fluctuations as shown by gage readings become more violent.

(5) The proportional accidental error of observing drop in pressure head between the section of beginning of convergence
upstream from the orifice and sections downstream from the orifice is in general least when the downstream section is at the point of greatest contraction. The error increases as the distance from this section is increased until the region of maximum pressure fluctuation is reached, and decreases thereafter as the downstream section approaches the section of resumed normal uniform flow.

(6) Except for $\frac{D}{d} = 1.2$ (the largest orifice used with each size of pipe), there is no indication of a variation between the general behavior of the flow passing through the orifice used with one size of pipe and that passing the corresponding orifices used with other sizes of pipe. That is, for a particular value of $\frac{D}{d}$, except $\frac{D}{d} = 1.2$, there is no indication that the curve showing the pressure variation for the 4-inch pipe should not coincide with that for the 6-inch pipe and for the 12-inch pipe. For $\frac{D}{d} = 1.2$ there is evidence of considerable variation, though whether or not this is to any considerable extent due to size of pipe is problematical.

The preceding deductions indicate that, for the purpose of flow measurement, gage readings of drop in pressure should be taken with gage connections at the section of beginning of convergence or upstream therefrom and at the section of greatest contraction. The distances to these sections, as far as effect on measurement of drop in pressure head is concerned, may be considered as 0.8 $D$ upstream from the orifice and 0.4 $D$ downstream from the orifice. In the tests to determine the relation between drop in pressure and discharge these distances were used.

12. Relation between Drop in Pressure Head and Discharge.—Since the use of the pipe orifice as a flow measuring device depends upon the proper relations between the drop in pressure head and the velocity (or rate of discharge) a wide range of tests was made to determine their relation after the preliminary experiments had shown the proper arrangement of the apparatus as already discussed.
FIG. 4. PIPE CONNECTIONS NEAR ORIFICE
Fig. 5. Differential Gages
The pipe orifice for measuring flow of water

For various rates of flow the discharge was measured during an observed time interval and the drop in pressure head was read from the differential gage. The velocities in the pipe ranged from 0.01 ft. per sec. with the smallest orifice of each series to 24 ft. per sec. with the largest orifice of the 4-in. series; the drop in pressure ranged from 0.01 ft. to 56 ft. On the average 30 observations for as many rates of flow were made for each size of orifice.

Fig. 4 shows the gage connections with the pipe at the two sections adjacent to the orifice, the distances to these sections being 0.8

| Table 3 |
| Sample Data |
| Orifices in 4 in. pipe |
| Head in ft. of water. | Time in sec. | Discharge in cu. ft. per sec. |

<table>
<thead>
<tr>
<th>Obs. No.</th>
<th>Net Wt.</th>
<th>Cor. Time</th>
<th>Lost Head</th>
<th>Drop in Pressure Head</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orifice 1.67 in. diameter.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>183</td>
<td>345</td>
<td>240</td>
<td>0.073</td>
<td>0.0088</td>
<td>0.0300</td>
</tr>
<tr>
<td>184</td>
<td>394</td>
<td>254</td>
<td>0.088</td>
<td>0.0104</td>
<td>0.0247</td>
</tr>
<tr>
<td>185</td>
<td>414</td>
<td>240</td>
<td>0.105</td>
<td>0.0127</td>
<td>0.0276</td>
</tr>
<tr>
<td>186</td>
<td>332</td>
<td>180</td>
<td>0.123</td>
<td>0.0151</td>
<td>0.0295</td>
</tr>
<tr>
<td>187</td>
<td>447</td>
<td>221</td>
<td>0.144</td>
<td>0.0174</td>
<td>0.0323</td>
</tr>
<tr>
<td>188</td>
<td>534</td>
<td>240</td>
<td>0.172</td>
<td>0.0213</td>
<td>0.0356</td>
</tr>
<tr>
<td>189</td>
<td>1076</td>
<td>420</td>
<td>0.229</td>
<td>0.0283</td>
<td>0.0410</td>
</tr>
<tr>
<td>190</td>
<td>525</td>
<td>180</td>
<td>0.263</td>
<td>0.0360</td>
<td>0.0467</td>
</tr>
<tr>
<td>191</td>
<td>583</td>
<td>170</td>
<td>0.284</td>
<td>0.0434</td>
<td>0.0519</td>
</tr>
<tr>
<td>192</td>
<td>660</td>
<td>180</td>
<td>0.468</td>
<td>0.0585</td>
<td>0.0658</td>
</tr>
<tr>
<td>193</td>
<td>731</td>
<td>182</td>
<td>0.591</td>
<td>0.0738</td>
<td>0.0698</td>
</tr>
<tr>
<td>194</td>
<td>830</td>
<td>180</td>
<td>0.700</td>
<td>0.0830</td>
<td>0.0746</td>
</tr>
<tr>
<td>195</td>
<td>938</td>
<td>180</td>
<td>0.955</td>
<td>1.18</td>
<td>0.0834</td>
</tr>
<tr>
<td>196</td>
<td>977</td>
<td>165</td>
<td>1.22</td>
<td>1.52</td>
<td>0.0948</td>
</tr>
<tr>
<td>197</td>
<td>912</td>
<td>132</td>
<td>1.68</td>
<td>2.05</td>
<td>0.110</td>
</tr>
<tr>
<td>198</td>
<td>960</td>
<td>122</td>
<td>2.21</td>
<td>2.76</td>
<td>0.126</td>
</tr>
<tr>
<td>199</td>
<td>1315</td>
<td>160</td>
<td>3.17</td>
<td>3.95</td>
<td>0.152</td>
</tr>
<tr>
<td>200</td>
<td>1739</td>
<td>180</td>
<td>3.26</td>
<td>4.30</td>
<td>0.155</td>
</tr>
<tr>
<td>201</td>
<td>1884</td>
<td>179</td>
<td>3.50</td>
<td>4.76</td>
<td>0.165</td>
</tr>
<tr>
<td>202</td>
<td>1857</td>
<td>164</td>
<td>4.45</td>
<td>5.48</td>
<td>0.181</td>
</tr>
<tr>
<td>203</td>
<td>1864</td>
<td>149</td>
<td>5.36</td>
<td>6.68</td>
<td>0.199</td>
</tr>
<tr>
<td>204</td>
<td>1862</td>
<td>130</td>
<td>6.50</td>
<td>8.27</td>
<td>0.219</td>
</tr>
<tr>
<td>205</td>
<td>1825</td>
<td>120</td>
<td>7.98</td>
<td>9.97</td>
<td>0.244</td>
</tr>
<tr>
<td>206</td>
<td>1821</td>
<td>106</td>
<td>10.1</td>
<td>12.7</td>
<td>0.276</td>
</tr>
<tr>
<td>207</td>
<td>3256</td>
<td>174</td>
<td>12.9</td>
<td>15.9</td>
<td>0.298</td>
</tr>
<tr>
<td>208</td>
<td>3373</td>
<td>155</td>
<td>16.7</td>
<td>20.6</td>
<td>0.348</td>
</tr>
<tr>
<td>209</td>
<td>3385</td>
<td>140</td>
<td>20.3</td>
<td>25.4</td>
<td>0.387</td>
</tr>
<tr>
<td>210</td>
<td>3129</td>
<td>120</td>
<td>23.7</td>
<td>29.5</td>
<td>0.417</td>
</tr>
</tbody>
</table>

| Orifice 2.00 in. diameter. |

| Orifice 2.00 in. diameter. |

<table>
<thead>
<tr>
<th>Obs. No.</th>
<th>Net Wt.</th>
<th>Cor. Time</th>
<th>Lost Head</th>
<th>Drop in Pressure Head</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>211</td>
<td>252</td>
<td>360</td>
<td>0.008</td>
<td>0.009</td>
<td>0.0112</td>
</tr>
<tr>
<td>212</td>
<td>301</td>
<td>360</td>
<td>0.011</td>
<td>0.013</td>
<td>0.0134</td>
</tr>
<tr>
<td>213</td>
<td>223</td>
<td>360</td>
<td>0.013</td>
<td>0.015</td>
<td>0.0144</td>
</tr>
<tr>
<td>214</td>
<td>284</td>
<td>300</td>
<td>0.018</td>
<td>0.018</td>
<td>0.0152</td>
</tr>
<tr>
<td>215</td>
<td>510</td>
<td>484</td>
<td>0.017</td>
<td>0.022</td>
<td>0.0172</td>
</tr>
<tr>
<td>216</td>
<td>246</td>
<td>200</td>
<td>0.020</td>
<td>0.026</td>
<td>0.0197</td>
</tr>
<tr>
<td>217</td>
<td>247</td>
<td>230</td>
<td>0.021</td>
<td>0.029</td>
<td>0.0217</td>
</tr>
<tr>
<td>218</td>
<td>653</td>
<td>490</td>
<td>0.030</td>
<td>0.039</td>
<td>0.0223</td>
</tr>
<tr>
<td>219</td>
<td>818</td>
<td>560</td>
<td>0.034</td>
<td>0.044</td>
<td>0.0234</td>
</tr>
<tr>
<td>220</td>
<td>578</td>
<td>560</td>
<td>0.040</td>
<td>0.060</td>
<td>0.0279</td>
</tr>
</tbody>
</table>
TABLE 3 (Continued)

SAMPLE DATA
Orifices in 12-in. pipe

<table>
<thead>
<tr>
<th>Obs. No.</th>
<th>Net Wt.</th>
<th>Cor. Time</th>
<th>Head</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>613a</td>
<td>294</td>
<td>600</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>614a</td>
<td>210</td>
<td>500</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>615a</td>
<td>198</td>
<td>400</td>
<td>0.017</td>
<td>0.018</td>
</tr>
<tr>
<td>616a</td>
<td>205</td>
<td>300</td>
<td>0.021</td>
<td>0.022</td>
</tr>
<tr>
<td>617</td>
<td>200</td>
<td>330</td>
<td>0.026</td>
<td>0.029</td>
</tr>
<tr>
<td>618</td>
<td>216</td>
<td>300</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>619</td>
<td>202</td>
<td>201</td>
<td>0.042</td>
<td>0.044</td>
</tr>
<tr>
<td>620</td>
<td>203</td>
<td>241</td>
<td>0.050</td>
<td>0.052</td>
</tr>
<tr>
<td>621</td>
<td>215</td>
<td>215</td>
<td>0.067</td>
<td>0.067</td>
</tr>
<tr>
<td>622</td>
<td>255</td>
<td>500</td>
<td>0.070</td>
<td>0.080</td>
</tr>
<tr>
<td>623</td>
<td>375</td>
<td>332</td>
<td>0.090</td>
<td>0.090</td>
</tr>
<tr>
<td>624</td>
<td>342</td>
<td>240</td>
<td>0.112</td>
<td>0.112</td>
</tr>
<tr>
<td>625</td>
<td>300</td>
<td>241</td>
<td>0.135</td>
<td>0.135</td>
</tr>
<tr>
<td>626</td>
<td>372</td>
<td>240</td>
<td>0.176</td>
<td>0.176</td>
</tr>
<tr>
<td>627</td>
<td>347</td>
<td>199</td>
<td>0.216</td>
<td>0.216</td>
</tr>
<tr>
<td>628</td>
<td>392</td>
<td>199</td>
<td>0.274</td>
<td>0.277</td>
</tr>
<tr>
<td>629</td>
<td>448</td>
<td>200</td>
<td>0.330</td>
<td>0.333</td>
</tr>
<tr>
<td>630</td>
<td>497</td>
<td>200</td>
<td>0.428</td>
<td>0.437</td>
</tr>
<tr>
<td>631</td>
<td>517</td>
<td>191</td>
<td>0.516</td>
<td>0.523</td>
</tr>
<tr>
<td>632</td>
<td>585</td>
<td>191</td>
<td>0.663</td>
<td>0.675</td>
</tr>
<tr>
<td>633</td>
<td>599</td>
<td>180</td>
<td>0.713</td>
<td>0.710</td>
</tr>
<tr>
<td>634</td>
<td>650</td>
<td>180</td>
<td>0.915</td>
<td>0.940</td>
</tr>
<tr>
<td>635</td>
<td>730</td>
<td>184</td>
<td>1.12</td>
<td>1.14</td>
</tr>
<tr>
<td>636</td>
<td>630</td>
<td>179</td>
<td>1.50</td>
<td>1.53</td>
</tr>
<tr>
<td>637</td>
<td>1040</td>
<td>292</td>
<td>1.86</td>
<td>1.91</td>
</tr>
<tr>
<td>638</td>
<td>1812</td>
<td>260</td>
<td>2.39</td>
<td>2.44</td>
</tr>
<tr>
<td>639</td>
<td>1842</td>
<td>240</td>
<td>2.97</td>
<td>3.04</td>
</tr>
<tr>
<td>640</td>
<td>1725</td>
<td>240</td>
<td>3.66</td>
<td>3.72</td>
</tr>
<tr>
<td>641</td>
<td>1644</td>
<td>200</td>
<td>4.79</td>
<td>4.89</td>
</tr>
<tr>
<td>642</td>
<td>1679</td>
<td>180</td>
<td>6.18</td>
<td>6.31</td>
</tr>
<tr>
<td>643</td>
<td>1787</td>
<td>155</td>
<td>7.88</td>
<td>8.04</td>
</tr>
<tr>
<td>644</td>
<td>3286</td>
<td>215</td>
<td>11.5</td>
<td>11.7</td>
</tr>
<tr>
<td>645</td>
<td>3318</td>
<td>155</td>
<td>15.9</td>
<td>16.2</td>
</tr>
<tr>
<td>646</td>
<td>1800</td>
<td>1084</td>
<td>21.2</td>
<td>21.6</td>
</tr>
<tr>
<td>647</td>
<td>3254</td>
<td>1644</td>
<td>27.2</td>
<td>27.8</td>
</tr>
<tr>
<td>649</td>
<td>3110</td>
<td>138</td>
<td>36.2</td>
<td>36.9</td>
</tr>
<tr>
<td>650</td>
<td>3398</td>
<td>145</td>
<td>41.4</td>
<td>42.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Obs. No.</th>
<th>Net Wt.</th>
<th>Cor. Time</th>
<th>Head</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>651</td>
<td>224</td>
<td>360</td>
<td>0.009</td>
<td>0.010</td>
</tr>
<tr>
<td>652</td>
<td>241</td>
<td>300</td>
<td>0.012</td>
<td>0.013</td>
</tr>
<tr>
<td>653</td>
<td>206</td>
<td>240</td>
<td>0.016</td>
<td>0.018</td>
</tr>
<tr>
<td>654</td>
<td>233</td>
<td>270</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>655</td>
<td>238</td>
<td>240</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>656</td>
<td>246</td>
<td>180</td>
<td>0.037</td>
<td>0.040</td>
</tr>
<tr>
<td>657</td>
<td>287</td>
<td>180</td>
<td>0.056</td>
<td>0.090</td>
</tr>
</tbody>
</table>

D upstream and 0.4 D downstream from the orifice and there being two pressure openings at diametrically opposite points at each section. Fig. 5 shows the differential gages with connecting hose. The two gages on the left, one for mercury, the other for water, are connected to the sections adjacent to the orifice and register the drop in pressure head; the two gages on the right register the lost head due to the orifice plus
## Table 3 (Concluded)

**Sample Data**

<table>
<thead>
<tr>
<th>Orifices in 12-in. pipe</th>
<th>Head in ft. of water</th>
<th>Time in sec.</th>
<th>Discharge in cu. ft. per sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs. No.</td>
<td>Initial</td>
<td>Final</td>
<td>Net</td>
</tr>
<tr>
<td>Orifice 6.00 in. diameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>783</td>
<td>48.2</td>
<td>167.3</td>
<td>119.1</td>
</tr>
<tr>
<td>784</td>
<td>54.7</td>
<td>170.3</td>
<td>115.6</td>
</tr>
<tr>
<td>785</td>
<td>57.7</td>
<td>169.3</td>
<td>110.6</td>
</tr>
<tr>
<td>786</td>
<td>54.5</td>
<td>180.4</td>
<td>134.9</td>
</tr>
<tr>
<td>787</td>
<td>53.9</td>
<td>200.9</td>
<td>147.6</td>
</tr>
<tr>
<td>788</td>
<td>57.2</td>
<td>209.6</td>
<td>152.4</td>
</tr>
<tr>
<td>789</td>
<td>45.1</td>
<td>193.7</td>
<td>148.6</td>
</tr>
<tr>
<td>790</td>
<td>43.5</td>
<td>177.7</td>
<td>134.2</td>
</tr>
<tr>
<td>791</td>
<td>37.0</td>
<td>177.0</td>
<td>140.0</td>
</tr>
<tr>
<td>792</td>
<td>13.6</td>
<td>170.0</td>
<td>177.3</td>
</tr>
<tr>
<td>793</td>
<td>14.1</td>
<td>187.9</td>
<td>173.8</td>
</tr>
<tr>
<td>794</td>
<td>1.4</td>
<td>204.1</td>
<td>205.5</td>
</tr>
<tr>
<td>795</td>
<td>15.5</td>
<td>181.3</td>
<td>168.8</td>
</tr>
<tr>
<td>796</td>
<td>4.4</td>
<td>203.9</td>
<td>203.5</td>
</tr>
<tr>
<td>797</td>
<td>6.8</td>
<td>220.6</td>
<td>219.8</td>
</tr>
<tr>
<td>798</td>
<td>11.0</td>
<td>204.5</td>
<td>193.5</td>
</tr>
<tr>
<td>799</td>
<td>2.3</td>
<td>236.6</td>
<td>234.3</td>
</tr>
<tr>
<td>Orifice 8.00 in. diameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs. No.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge given in pounds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>1443</td>
<td>122</td>
<td>0.005</td>
</tr>
<tr>
<td>801</td>
<td>1771</td>
<td>122</td>
<td>0.008</td>
</tr>
<tr>
<td>802</td>
<td>3245</td>
<td>235</td>
<td>0.007</td>
</tr>
<tr>
<td>803</td>
<td>3187</td>
<td>200</td>
<td>0.019</td>
</tr>
<tr>
<td>804</td>
<td>3197</td>
<td>170</td>
<td>0.013</td>
</tr>
<tr>
<td>805</td>
<td>3148</td>
<td>162</td>
<td>0.015</td>
</tr>
<tr>
<td>Discharge in Cubic Feet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>806</td>
<td>55.6</td>
<td>165.4</td>
<td>109.8</td>
</tr>
<tr>
<td>807</td>
<td>57.8</td>
<td>169.1</td>
<td>111.3</td>
</tr>
<tr>
<td>808</td>
<td>60.3</td>
<td>169.8</td>
<td>109.5</td>
</tr>
<tr>
<td>809</td>
<td>11.3</td>
<td>167.4</td>
<td>156.1</td>
</tr>
<tr>
<td>810</td>
<td>50.5</td>
<td>167.2</td>
<td>116.7</td>
</tr>
<tr>
<td>811</td>
<td>48.2</td>
<td>170.6</td>
<td>122.4</td>
</tr>
<tr>
<td>812</td>
<td>45.2</td>
<td>176.3</td>
<td>131.1</td>
</tr>
<tr>
<td>813</td>
<td>52.7</td>
<td>182.1</td>
<td>129.4</td>
</tr>
<tr>
<td>814</td>
<td>42.8</td>
<td>205.8</td>
<td>163.0</td>
</tr>
<tr>
<td>815</td>
<td>51.1</td>
<td>202.4</td>
<td>141.3</td>
</tr>
<tr>
<td>816</td>
<td>41.3</td>
<td>215.7</td>
<td>174.4</td>
</tr>
<tr>
<td>817</td>
<td>36.8</td>
<td>225.2</td>
<td>188.9</td>
</tr>
<tr>
<td>818</td>
<td>35.4</td>
<td>223.1</td>
<td>187.7</td>
</tr>
<tr>
<td>819</td>
<td>39.4</td>
<td>225.3</td>
<td>186.9</td>
</tr>
<tr>
<td>820</td>
<td>27.4</td>
<td>231.2</td>
<td>193.8</td>
</tr>
<tr>
<td>821</td>
<td>25.9</td>
<td>236.7</td>
<td>210.8</td>
</tr>
<tr>
<td>822</td>
<td>7.1</td>
<td>230.5</td>
<td>223.4</td>
</tr>
</tbody>
</table>

The loss due to pipe friction within the length between gage connections. The lost head will be discussed in section 16.

A sample of the data thus obtained is shown in Table 3. The values of lost head there recorded have been corrected for pipe friction.
The data of the tests are plotted logarithmically in Figs. 6, 7 and 8, the observed drop in pressure head in feet being plotted against measured discharge in cubic feet per second. The lines which have been drawn through the mean of the plotted points are seen to be straight and very nearly parallel. It will also be noted that the curves for one series bear the same general relation to one another as do the curves for the other two series.

The mean of the measured slopes of the 24 curves varies only slightly from 2.00. A study of the curves indicates that the variation of the slopes of the individual curves from the mean value is partly
accidental. Since the curves are plotted to logarithmic scale and have a slope of 2, $h_b$ may be said to vary as $V^2$, which is in accord with the theoretical expression, equation (1) p. 12. To make the theoretical equation exactly fit the experimental curves it must be assumed that for a particular size of orifice and pipe the coefficient of discharge decreases slightly as the drop in pressure head increases, as may be seen in Table 4.

The values of the coefficients of discharge in Table 4 were obtained by substituting in equation (1) values of $h_b$ and $V = \frac{Q}{A}$ taken from the experimental curves. It will be seen that for a particular value of $\frac{D}{d}$
**Fig. 8. Experimental Discharge Curves—12-inch Pipe**

**Table 4**

**Coefficient of Discharge—C**

<table>
<thead>
<tr>
<th>$D$</th>
<th>4-in. Pipe</th>
<th>6-in. Pipe</th>
<th>12-in. Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$b_{=0.1}$</td>
<td>$h_{=1.00}$</td>
<td>$h_{=50}$</td>
</tr>
<tr>
<td>1.22</td>
<td>0.771</td>
<td>0.760</td>
<td>0.760</td>
</tr>
<tr>
<td>1.52</td>
<td>0.670</td>
<td>0.663</td>
<td>0.651</td>
</tr>
<tr>
<td>2.03</td>
<td>0.513</td>
<td>0.528</td>
<td>0.517</td>
</tr>
<tr>
<td>2.45</td>
<td>0.622</td>
<td>0.619</td>
<td>0.609</td>
</tr>
<tr>
<td>3.05</td>
<td>0.617</td>
<td>0.614</td>
<td>0.606</td>
</tr>
<tr>
<td>4.07</td>
<td>0.615</td>
<td>0.615</td>
<td>0.608</td>
</tr>
<tr>
<td>6.10</td>
<td>0.626</td>
<td>0.624</td>
<td>0.618</td>
</tr>
<tr>
<td>8.14</td>
<td>0.638</td>
<td>0.636</td>
<td>0.630</td>
</tr>
</tbody>
</table>
the coefficient of discharge not only decreases slightly as the drop in pressure head increases but also decreases as the diameter of the pipe increases.

For a better understanding of the general behavior of the coefficient of discharge, and also that the coefficient of discharge may be determined readily for other values of $\frac{D}{d}$ than those of the experiments, the data of Table 4 for the 4-inch pipe are shown graphically by the two upper curves of Fig. 9, values of the coefficients being plotted against $\frac{D}{d}$. The two curves—the full line for $h_b=0.1$ ft. and the dash line for $h_b=50$ ft.—are intended to show the extremes of the coefficients which may possibly be used. For $\frac{D}{d}$ greater than 3.0 the coefficient of discharge increases nearly as a straight line, a peculiarity which may perhaps be explained through the fact that as $\frac{D}{d}$ increases the distance from the wall of the pipe to the periphery of the jet at the section of greatest contraction also increases and there is consequently less likelihood of the pressure at the wall of the pipe being the same as that which exists at the periphery of the jet at the section of greatest contraction. As $\frac{D}{d}$ decreases from 3.00 the coefficient of discharge increases, and the rate at which the coefficient changes for small values of $\frac{D}{d}$ still further emphasizes the impracticability of attempting to make precise measurements of discharge when the diameter of the orifice is greater than two-thirds the diameter of the pipe.

The $C$ curves for the 4-inch pipe are typical of those for the 6-inch and 12-inch for the lower values of $h_b$ and $\frac{D}{d}$, but as $h_b$ becomes larger the rate of increase of $C$ diminishes for the higher values of $\frac{D}{d}$. The two lower curves of Fig. 9 illustrate this change in rate of increase of $C$.

13. *Simplified Equations for Velocity and Discharge.*—The theoretical equation for the determination of velocity in the pipe in terms
Fig. 9. Coefficients of Discharge
of the drop of pressure head (equation (2), p. 12) may be put in the form

\[ V = K \sqrt{\frac{2g}{C^2}} \sqrt{\frac{D}{d}} - h_b \]

in which

\[ K = \sqrt{\frac{2g}{C^2}} \sqrt{\frac{D}{d}} - 1 \]

The expression for the rate of discharge then is

\[ Q = AK \sqrt{\frac{2g}{C^2}} \sqrt{\frac{D}{d}} - h_b \]

Within the range of the drop in pressure likely to be used in practice, \( K \) may with small error be regarded as a constant for a particular size of pipe and orifice. To simplify the work of computing velocities, values of \( K \) for various sizes of pipes are given in Table 5. For convenience, the term \( K \) will be called the velocity modulus. Some of the values of the velocity modulus have been carried to one more sig-

<table>
<thead>
<tr>
<th>( D )</th>
<th>( \frac{d}{d} )</th>
<th>4-in. Pipe</th>
<th>5-in. Pipe</th>
<th>6-in. Pipe</th>
<th>8-in. Pipe</th>
<th>10-in. Pipe</th>
<th>12-in. Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>1.275</td>
<td>1.250</td>
<td>1.240</td>
<td>1.240</td>
<td>1.240</td>
<td>1.240</td>
<td></td>
</tr>
<tr>
<td>2.10</td>
<td>1.150</td>
<td>1.123</td>
<td>1.111</td>
<td>1.110</td>
<td>1.110</td>
<td>1.110</td>
<td></td>
</tr>
<tr>
<td>2.20</td>
<td>1.030</td>
<td>1.015</td>
<td>1.010</td>
<td>1.010</td>
<td>1.010</td>
<td>1.010</td>
<td></td>
</tr>
<tr>
<td>2.30</td>
<td>0.944</td>
<td>0.930</td>
<td>0.925</td>
<td>0.925</td>
<td>0.925</td>
<td>0.925</td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>0.855</td>
<td>0.850</td>
<td>0.845</td>
<td>0.845</td>
<td>0.845</td>
<td>0.845</td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td>0.798</td>
<td>0.795</td>
<td>0.799</td>
<td>0.799</td>
<td>0.799</td>
<td>0.799</td>
<td></td>
</tr>
<tr>
<td>2.60</td>
<td>0.739</td>
<td>0.735</td>
<td>0.730</td>
<td>0.729</td>
<td>0.729</td>
<td>0.729</td>
<td></td>
</tr>
<tr>
<td>2.70</td>
<td>0.684</td>
<td>0.672</td>
<td>0.667</td>
<td>0.667</td>
<td>0.667</td>
<td>0.667</td>
<td></td>
</tr>
<tr>
<td>2.80</td>
<td>0.635</td>
<td>0.625</td>
<td>0.620</td>
<td>0.620</td>
<td>0.620</td>
<td>0.620</td>
<td></td>
</tr>
<tr>
<td>2.90</td>
<td>0.592</td>
<td>0.583</td>
<td>0.578</td>
<td>0.578</td>
<td>0.578</td>
<td>0.578</td>
<td></td>
</tr>
<tr>
<td>3.00</td>
<td>0.553</td>
<td>0.545</td>
<td>0.540</td>
<td>0.540</td>
<td>0.540</td>
<td>0.540</td>
<td></td>
</tr>
<tr>
<td>3.15</td>
<td>0.473</td>
<td>0.465</td>
<td>0.462</td>
<td>0.461</td>
<td>0.461</td>
<td>0.461</td>
<td></td>
</tr>
<tr>
<td>3.25</td>
<td>0.405</td>
<td>0.399</td>
<td>0.396</td>
<td>0.395</td>
<td>0.395</td>
<td>0.395</td>
<td></td>
</tr>
<tr>
<td>3.50</td>
<td>0.331</td>
<td>0.325</td>
<td>0.322</td>
<td>0.322</td>
<td>0.322</td>
<td>0.322</td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>0.310</td>
<td>0.305</td>
<td>0.303</td>
<td>0.302</td>
<td>0.302</td>
<td>0.302</td>
<td></td>
</tr>
<tr>
<td>4.50</td>
<td>0.244</td>
<td>0.230</td>
<td>0.235</td>
<td>0.235</td>
<td>0.235</td>
<td>0.235</td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td>0.197</td>
<td>0.184</td>
<td>0.192</td>
<td>0.192</td>
<td>0.192</td>
<td>0.192</td>
<td></td>
</tr>
<tr>
<td>5.50</td>
<td>0.165</td>
<td>0.161</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td>0.138</td>
<td>0.136</td>
<td>0.135</td>
<td>0.135</td>
<td>0.135</td>
<td>0.135</td>
<td></td>
</tr>
</tbody>
</table>
significant figure than the data may warrant in order to permit more nearly accurate interpolation. In interpolating for other values of \( \frac{D}{d} \) or other sizes of pipe than those shown it may be assumed that the velocity modulus varies as a straight line.

The computations for the velocity modulus were based on the coefficients of discharge for a drop in pressure head of 1.0 ft. as shown in Table 4 and by the curves of Figs. 9 and 10. (Fig. 10 is explained in the following section.) Since \( K \) varies as \( C \) and since \( C \) decreases as \( h_b \) increases, the values of the velocity modulus are for a large drop in pressure head slightly too large and for a small drop in pressure head slightly too small; but within the limits \( h_b = 0.1 \) ft. to \( h_b = 10 \) ft., which seem to be about the limits which would be found practicable under ordinary conditions of flow, the error introduced by use of Table 5 is negligible.

14. Application to Other Sizes of Pipes.—In order to use equation (2) or (4) for sizes of pipe other than those used in the experiments herein recorded it is important to determine the effect of the diameter of the pipe on the coefficient of discharge. The proper coefficient of discharge is obtained by applying a diameter factor, \( C_p \), which is the quantity by which the coefficient of discharge for a 6-inch pipe must be multiplied to produce the coefficient of discharge for a given size of pipe. The values of the diameter factor for various diameters of pipe are shown in Fig. 10. Since the curve is based on only

![Fig. 10. Diameter Factor](image-url)
three plotted points it is likely to be somewhat in error. Its use should
be confined to values of $\frac{D}{d}$ between 2 and 6 and between 1 ft. and 10
ft. for $h_b$ if accurate results are desired.

15. Empirical Relation between Velocity and Drop in Pressure Head.—From
the discharge curves of Figs. 6, 7, and 8 the following empirical equation has been derived for the velocity in terms of the
drop in pressure head,

$$V = 4.85 \frac{\sqrt{h_b}}{\left(\frac{D}{d}\right)^2 - \left(\frac{d}{D}\right)^3} \quad (6)$$

This equation has an advantage over the rational expression, equation (2), in that the variable coefficient of discharge is eliminated.
This empirical equation will give approximately the same results as
equation (2) for those values of $\frac{D}{d}$ which are recommended for use
in engineering practice, namely, for values of $\frac{D}{d}$ between 2 and 6.

16. Empirical Formula for Lost Head.—Since the amount of
lost head caused by the orifice may be an important factor in the selec-
tion of the orifice to be used, or even in accepting the pipe orifice
method of measuring the discharge, it is important to know the rela-
tion between the drop in pressure head and the lost head. In Fig. 5
the gages on the right registered the lost head due to the orifice plus
the loss due to pipe friction within the length between gage connec-
tions.

The results of the experiments to determine this relation indicate
that the rational expression, equation (3) p. 13, holds good when
the ratio $\frac{D}{d}$ is large but gives results which are increasingly too large
as $\frac{D}{d}$ decreases, until for $\frac{D}{d} = 1.2$ the lost head as computed by equation
(3) is about 3 per cent less than the lost head as determined by ex-
periment. In arriving at this conclusion, the coefficients of discharge
as determined from the experiments on drop in pressure head and
as shown in Table 4 were used in the rational expression and the coefficients of contraction employed were derived assuming a coefficient of velocity of 0.98.

Equation (3) is too complicated an expression to be used readily in computing. A simpler expression for the lost head and the discharge is given by the empirical equation

$$h_a = 0.0366 F \left[ \left( \frac{D}{d} \right)^2 - \frac{d}{D} \right]^{2.02} V^2 \quad (7)$$

in which $F$ is a factor depending on the size of pipe and having the values 0.98 for 4-inch pipe, 1.02 for 6-inch pipe and 1.04 for 12-inch pipe. This expression gives lost heads correct within about 2 per cent except when $\frac{D}{d}$ is less than 1.5. For $\frac{D}{d} = 1.2$ the expression gives results about 3 per cent too small.

A convenient expression for determining the lost head, having given the drop in pressure head, is given by the equation

$$h_a = 0.84 h_b \frac{\left[ \left( \frac{D}{d} \right)^2 - \frac{d}{D} \right]^{2.02}}{\left[ \left( \frac{D}{d} \right)^2 - \left( \frac{d}{D} \right)^3 \right]^{1.99}} = J h_b \quad (8)$$

The values of $J$ in the foregoing equation for given values of $h_b$ are shown by the curve in Fig. 11.

17. Choice of Orifice.—The choice of the size of orifice to be used under given conditions may depend upon four factors, the rate of flow in the pipe, the lost head that may be allowed, the desired precision of the discharge measurement, and the maximum drop in pressure head which the differential gage will register. Table 6 which shows approximate values of the drop in pressure head and the lost head for several velocities and values of $\frac{D}{d}$ is intended to be of assistance in estimating the size of orifice best adapted to particular requirements. In Fig. 12 the drop in pressure head for various ratios of $\frac{D}{d}$ is given in terms of the lost head.
FIG. 11. RELATION BETWEEN LOST HEAD AND DROP IN PRESSURE HEAD

FIG. 12. RELATION BETWEEN MAXIMUM DROP IN PRESSURE AND SIZE OF ORIFICE

The relative error in the observation of the drop in pressure head varies inversely as $\frac{D}{d}$ but for $\frac{D}{d}$ equal to 2.0 or greater the error may be reduced to a negligible quantity. There are other factors which make it advisable to use a diameter of orifice not greater than one-half that of the pipe when conditions will allow. If the magnitude of
the lost head is not an important factor, it is best that the drop in pressure head be greater than 1.0 ft. so that the relative error of measurement will be small, but the indications are that gage heights as small as 0.2 ft. may be measured with good results, provided the observer is experienced. Reliable observations may be taken with an orifice having a diameter two-thirds that of the pipe, but the probable error of reading the gage is likely to be several times what it is for the smaller orifices, even though the gage be carefully throttled. An orifice having a diameter much greater than two-thirds that of the pipe should not be used except for approximate discharge measurements.

As an illustrative example let it be required to measure the rate of discharge through an 8-inch pipe the velocity in which varies during the day through a large range, say from about 1 to 6 ft. per sec. Should the pipe-orifice method be used and, if so, what size of orifice should be installed? From Table 6 it will be noted that for $\frac{D}{d} = 2$ the drop in pressure head is 0.64 ft. for a velocity of 1 ft. per sec. in the pipe, with a lost head of 0.46 ft. Likewise the drop in pressure head is 23 ft. for a velocity of 6 ft. per sec. with a lost head of 17 ft. Assuming that a lost head of 10 ft. is the greatest that should be allowed and that both a water gage and a mercury gage would be used for a range in drop of pressure head of 23 ft., it is seen that an

### Table 6

**Approximate Values of Drop in Pressure and Lost Head**

$h_b =$ drop in pressure head in feet; $h_a =$ lost head in feet

<table>
<thead>
<tr>
<th>$V$</th>
<th>$\frac{D}{d} = 1.2$</th>
<th>$\frac{D}{d} = 1.5$</th>
<th>$\frac{D}{d} = 2.0$</th>
<th>$\frac{D}{d} = 2.5$</th>
<th>$\frac{D}{d} = 3.0$</th>
<th>$\frac{D}{d} = 4.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h_b$</td>
<td>$h_a$</td>
<td>$h_b$</td>
<td>$h_a$</td>
<td>$h_b$</td>
<td>$h_a$</td>
</tr>
<tr>
<td>0.2</td>
<td>0.12</td>
<td>0.09</td>
<td>0.16</td>
<td>0.12</td>
<td>0.41</td>
<td>0.33</td>
</tr>
<tr>
<td>0.5</td>
<td>0.17</td>
<td>0.10</td>
<td>0.04</td>
<td>0.56</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.38</td>
<td>2.6</td>
<td>1.9</td>
<td>6.5</td>
<td>5.3</td>
</tr>
<tr>
<td>2</td>
<td>0.37</td>
<td>0.12</td>
<td>1.5</td>
<td>0.8</td>
<td>5.8</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td>0.65</td>
<td>0.21</td>
<td>2.6</td>
<td>1.4</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>0.3</td>
<td>4.1</td>
<td>2.3</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>0.5</td>
<td>5.9</td>
<td>3.2</td>
<td>23</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>4.1</td>
<td>1.3</td>
<td>17</td>
<td>9</td>
<td>64</td>
<td>46</td>
</tr>
<tr>
<td>10</td>
<td>0.66</td>
<td>0.38</td>
<td>2.6</td>
<td>1.9</td>
<td>6.5</td>
<td>5.3</td>
</tr>
</tbody>
</table>
orifice larger than 4 in. should be selected. One with $\frac{D}{d} = 1.5$ gives a range in drop in pressure head from 0.17 to 5.9 ft, corresponding to a range in lost head of 0.09 to 3.2 ft. An orifice with $\frac{D}{d} = 1.5$ would give somewhat less nearly accurate results than one with $\frac{D}{d} = 2$ (as already discussed) but it would answer the purpose well, although perhaps it would be advisable to use a slightly larger orifice, one with $\frac{D}{d} = 1.6$ or $\frac{D}{d} = 1.75$.

18. **Computations for Discharge.**—For most precise computations use equation (2), p. 12, with coefficient of discharge taken from Table 4, p. 30. For sizes of pipe other than those for which coefficients are shown use the diameter factor as explained in section 14, p. 34. With $\frac{D}{d}$ from 1.5 to 6 and with care in making the observations, the error introduced may be kept lower than 2 per cent. With wider ranges of $\frac{D}{d}$ or with very high or low values in drop in pressure head this percentage will be increased, because of difficulties in reading the gage properly.

For less precise computations use equation (4) or equation (5), p. 33, with the proper velocity modulus taken from Table 5, p. 33. With pipe from 4 to 12 inches in diameter and with $\frac{D}{d}$ from 1.5 to 6, the maximum error introduced will be about 3 per cent. With wider ranges of $\frac{D}{d}$ or with very high or low values of drop in pressure head this percentage will be correspondingly increased.

The use of equation (6), p. 35, eliminates variable coefficients. For sizes of pipe from 4 to 12 inches, with $\frac{D}{d}$ from 2 to 4 the maximum error will not be greater than 3 per cent. With $\frac{D}{d}$ less than 2 or greater than 4 the error introduced may be 5 per cent or more.

Diagrams similar to Figs. 6, 7, and 8 may be constructed, from which the discharge for the more common sizes of pipe, with the proper
range of \( \frac{D}{d} \), may be obtained directly. The calculation, however, from equations (4) and (5) and Tables 6 and 7 is very simple.

To determine the lost head, having given \( \frac{D}{d} \) and the drop in pressure head, use equation (8), p. 36.

19. **Errors and Precautions.**—In the use of a flow measuring device it is important to know the source of the errors likely to be met and to know the precautions and limitations which if observed will help to reduce the errors.

It is important that the edges of the orifices be sharp and square. The orifice plates in the present tests were 3/16 inch thick, but there is no reason for believing that the coefficients derived from the experimental data would not apply equally well to orifices in plates of lesser thickness.

The orifice should be placed in a region where there is approximately uniform flow. This will necessitate the pipe upstream from the orifice being straight and free from abrupt changes in cross-sectional area for 10 diameters or more.

On account of the possibility of small openings becoming clogged it seems inadvisable to use gage connections having a diameter less than \( \frac{1}{4} \) inch, particularly for permanent installation.

It is important that all burr be removed and also that the nipple does not protrude beyond the inner surface of the pipe; for small projections, by altering flow conditions, are likely to produce a systematic error of considerable magnitude in the gage readings.

For \( \frac{D}{d} \) equal to 2.0 or greater a single nipple at each section will be sufficient. Although in the tests from which the coefficients of discharge were derived the sections at which nipples were placed were 0.8 \( D \) upstream from the orifice and 0.4 \( D \) downstream from the orifice, these distances may be altered somewhat without appreciably changing pressure conditions. (See Fig. 3, p. 20).

For \( \frac{D}{d} \) less than 2.0 two opposite nipples at each section produce more reliable gage readings than do the single nipples, the pair at each section being joined together as illustrated in Fig. 4, p. 23. The indications are that the distance from the orifice to the section
downstream from the orifice may not be appreciably altered from 0.4 $D$ and that the distance from the orifice to the section upstream from the orifice should not be less than 0.8 $D$. On account of pipe friction this latter distance should not greatly exceed 0.8 $D$, particularly for high velocities.

A differential gage of the U-tube type, similar to those shown in Fig. 5, p. 24, answers all the requirements, is simple to construct, and may be used with mercury or water. The gage board should be graduated to 0.01 ft. and the graduations should extend under the gage tubes. For flushing the gage and the connecting tubes, and for regulating the height of the air columns when water is the differential, there should be a pet cock at the end of each gage tube. Stop cocks for throttling the gage should be placed near the ends of the gage tubes as shown in Fig. 5.

A gage that may be quickly constructed in an emergency and the essential parts of which are easily obtainable and readily portable is shown in Fig. 13. The glass tubes need not be more than a foot

![Fig. 13. Emergency Differential Gage](image-url)
The piece of rubber tubing connecting the glass tubes makes it possible to adjust the relative height of the tubes to suit the drop in pressure head. The gage may be fixed to an ordinary leveling rod or may be fixed to a plain board and the gage height measured with the ordinary pocket rule. This form of gage is not suitable for high pressures on account of the difficulty of making tight joints.

If the pressure openings are in the upper side of the pipe, it is important that provision be made for removing air, which is likely to become pocketed on either side of the orifice and in the gage connections, without forcing it through the hose or pipe connecting the pressure openings with the gage. If there are no pressure openings in the upper side of the pipe, pet cocks should be inserted. When opposite openings are inserted at each section provision should be made for ascertaining whether or not the tubes are free from obstruction and full of water. Fig. 4, p. 23, illustrates an arrangement of valves and pet cocks which makes this possible.

Preliminary to taking observations, with water flowing in the pipe, all cocks should be opened and the pipe and gage connections should be flushed. It is important that there should be no air in the pipe in the vicinity of the orifice, nor in the gage connections, for the presence of air is likely to change radically the gage reading.

If the foregoing precautions are observed under favorable conditions, the rate of discharge as measured by a pipe orifice should be accurate within 2 per cent. This means compares favorably with many other methods of measuring water. For unfavorable conditions the accuracy of the method will be as great as with most other methods under similarly unfavorable conditions.
IV. Effect of Deviation from Standard Conditions

20. General Remarks.—With the possibilities of utilizing the relation between drop in pressure and discharge for determining the rate of discharge through a pipe line in mind, it is important that something should be known concerning the effect of slight deviations from the standard conditions under which the tests were made, either in the arrangement or design of the apparatus or in the methods of handling the apparatus. To this end series of tests were made: (1) with gage connections fully opened and then with gage throttled, (2) with a single gage connection at each section, first with the nipple inserted in the upper side of the pipe and then in the under side, (3) with 1/4-inch eccentricity between center of orifice and center of pipe, first with a single nipple at each section, and then with the standard connection of two opposite nipples at each section, (4) with 45 degree bevel-edged orifices, the bevel facing upstream.

21. Throttling.—The purpose of throttling is to reduce the effect of momentary pressure fluctuations, thereby causing, for a constant discharge, the fluid in the columns of the differential gage to remain in a nearly stationary position. The experiments indicate that for values of $\frac{D}{d}$ of 2 or greater, when there are no systematic surges along the pipe line (such as might be caused by pump action), there is no appreciable reduction in the magnitude of the accidental errors of observing brought about by throttling; but for $\frac{D}{d}$ less than 2, when the region of greatly disturbed flow (to which reference has previously been made) is at or near the section of greatest contraction, the accidental errors may be reduced to 20 or 25 per cent of what they are with gage connections fully open. The results of the tests also make it clear that systematic errors are likely to enter into the gage readings unless the throttling is done very carefully. If the gage is throttled too much and a change in the rate of flow takes place, it is likely to be several minutes before the columns become fully adjusted to the change in pressure. If the throttling is done
quickly, a gage reading taken immediately after is not likely to rep-
resent the mean difference in pressure head.

Briefly summed up, the experience of the observers warrants the
following suggestions:

(1) Throttle only when necessary, which in general will
be for values of $\frac{D}{d}$ less than 2, unless there are systematic surges
along the pipe line.

(2) Throttling too much is often worse than not throttling
at all, particularly if the rate of discharge is variable. Accurate
observations may be taken when there is a considerable fluctuation
in the heights of the gage columns.

(3) When throttling, best results are to be obtained if the
throttle cocks are opened prior to each observation and simul-
taneously and slowly closed the desired amount. It is important
that there should be no leaks in the gage connections. A leakage
of a few drops per minute from the throttle cock is likely to
produce a large error in gage reading.

(4) When using the water gage, observations may be most
nearly accurately taken when the gage is so throttled that the
two water columns fluctuate the same amount and in unison. In
general this arrangement will require that the gage column con-
nection for the section of greatest contraction be throttled more
than that for the section of beginning of convergence.

22. Position and Number of Gage Connections.—The tests to
determine the effect of the position and number of gage connections
warrant the following statements:

(1) If the orifice is concentric with the pipe, a change in the
circumferential position of the pipe nipples inserted at the section
of beginning of convergence and the section of greatest contra-
tion will cause no variation in gage readings. If only one nipple
is to be inserted at each section, there is an advantage in placing
it in the under side of the pipe if air is present in the discharge,
and in the upper side of the pipe if sediment is being carried.

(2) For $\frac{D}{d}$ equal to 2 or more there is no material advantage
in having more than one pressure opening at each section. For 
\[ \frac{D}{d} \] less than 2 the momentary fluctuations in pressure, as registered by the gage, may be appreciably reduced by having two opposite openings at each section, these being connected as shown in Fig. 4, p. 23. It seems probable that additional openings would still further reduce the gage fluctuations.

23. Eccentricity.—The tests to determine the effect of eccentricity were made on only the 4-inch pipe. The eccentricity was \( \frac{1}{4} \) inch and the displacement of the orifice was vertical. The apparatus was so arranged that the gage could be made to register the difference in pressure obtained for the two sections by connecting to the differential gage (a) the openings in the top of the pipe, (b) the openings in the bottom of the pipe, and (c) all four openings.

The results indicate that regardless of the size of orifice an eccentricity of as much as \( \frac{D}{16} \) will produce no effect on gage readings, provided the gage is connected to two opposite pressure openings at each section. But for \( \frac{D}{d} \) less than 2 the gage readings will be changed considerably when the gage is connected to a single pressure opening at each section. For \( \frac{D}{d} = 1.5 \) this change is about 4 per cent, and for \( \frac{D}{d} = 1.2 \), about 18 per cent. It seems probable that a corresponding eccentricity with other sizes of pipe would produce a similar effect. Considering the difficulties of ascertaining whether or not the orifice is properly centered under the ordinary conditions of practice, the necessity for gage connections on opposite sides of the pipe at each section, when \( \frac{D}{d} \) is less than 2, will be readily appreciated.

The effect of small longitudinal displacements of the gage connections is well illustrated by the curves of Fig. 3, p. 20. It is evident that for \( \frac{D}{d} \) less than 2, in order that no measurable change in the gage readings be produced, no considerable change in the longitudinal position of the pressure openings for the section of beginning of convergence may be made, nor may the pressure openings for the section
of greatest contraction be placed nearer the orifice than four-tenths the diameter of the pipe.

24. **Bevel-edged Orifices.**—The method of conducting tests with bevel-edged orifices was identical with that used in determining the relation between drop in pressure and discharge for thin square-edged orifices. Tests were made on 4-inch and 6-inch pipe with five sizes of orifice for each size of pipe. For each of the two series of tests the ratios of diameter of pipe to diameter of orifice were 1.22, 1.52, 2.03, 3.04, and 6.08.

The orifices were cut in 3/16-inch plates with the upstream edge on a 45-degree bevel. The thickness of metal at the small diameter of each orifice was 1/32 inch, and the large diameter was 5/16 inch greater than the small diameter.

In instituting the tests the thought was that the effect of the beveled edge might go to produce a coefficient of discharge less affected by small changes in \( \frac{D}{d} \) as the diameter of the orifice approaches that of the pipe, and thus make it practicable, with high velocities, to use a larger sized orifice than the experiments with thin-plate orifices indicate may be used with precision.

<table>
<thead>
<tr>
<th>( D )</th>
<th>Coef. of Discharge</th>
<th>( h_b = 0.01 )</th>
<th>( h_b = 0.1 )</th>
<th>( h_b = 1.0 )</th>
<th>( h_b = 10 )</th>
<th>( h_b = 50 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.22</td>
<td>0.870</td>
<td>0.852</td>
<td>0.832</td>
<td>0.811</td>
<td>0.800</td>
<td></td>
</tr>
<tr>
<td>1.52</td>
<td>0.802</td>
<td>0.784</td>
<td>0.765</td>
<td>0.747</td>
<td>0.738</td>
<td></td>
</tr>
<tr>
<td>2.03</td>
<td>0.773</td>
<td>0.759</td>
<td>0.745</td>
<td>0.731</td>
<td>0.724</td>
<td></td>
</tr>
<tr>
<td>3.04</td>
<td>0.753</td>
<td>0.741</td>
<td>0.730</td>
<td>0.718</td>
<td>0.713</td>
<td></td>
</tr>
<tr>
<td>6.08</td>
<td>0.756</td>
<td>0.750</td>
<td>0.745</td>
<td>0.739</td>
<td>0.737</td>
<td></td>
</tr>
</tbody>
</table>

The coefficients of discharge, deduced from discharge curves similar to those of Figs. 6 and 7, pp. 28 and 29, are shown in Table 7. A comparison of these coefficients with corresponding values in Table 4, p. 30, will show that the effect of beveling has been materially to increase the coefficients of discharge and also to produce a coefficient of discharge that, as the drop in pressure head increases and as the size of pipe increases, decreases much more rapidly. In Fig. 14 the coeffi-
Fig. 14. Coefficients of Discharge for Bevel-edged Orifices

Coefficients of Table 7 for $h_b = 0.01$ ft. and $h_b = 10$ ft. are plotted against values of $\frac{D}{d}$. A comparison of the curves drawn through these points with corresponding curves for square-edged orifices, Fig. 9, p. 32, will
still further emphasize the extreme variability of the coefficients of discharge under consideration. As an offset to these undesirable characteristics, for a given change in the value of $\frac{D}{d}$ when that ratio is less than 2, there is considerably less variation in the coefficient of discharge for the bevel-edged orifice than for the square-edged orifice. This statement is especially true for values of $\frac{D}{d}$ less than 1.5, where the rate of change for the bevel-edged orifice is about two-thirds that for the square-edged orifice.

It is worth noting that the coefficient of discharge for each orifice approaches that for the corresponding square-edged orifice as the drop in pressure head increases, and that the rate of this increase becomes greater as $\frac{D}{d}$ decreases and becomes greater as the diameter of the pipe increases. For example, for the 4-inch pipe and $\frac{D}{d} = 2.03$ the variation between the two coefficients of discharge is 17 per cent when $h_b = 0.1$ ft. and 15 per cent when $h_b = 50$ ft.; for the 6-inch and $\frac{D}{d} = 2.03$ the variation is 14 per cent when $h_b = 0.1$ ft. and 12 per cent when $h_b = 50$ ft.

A study of the observations indicates that the accidental errors of reading the gage are about the same for the bevel-edged orifice as for the square-edged orifice. The systematic errors, however, or those which will not be eliminated by increasing the number of observations, are those to which most attention must be given; and among the sources of systematic error when $\frac{D}{d}$ is small, that source most likely to be productive of the greatest error in the computed discharge under the conditions of ordinary practice seems to be in the determination of the ratio $\frac{D}{d}$. Since for small values of $\frac{D}{d}$ the coefficient of discharge for bevel-edged orifices varies less for a given change in $\frac{D}{d}$ than does the coefficient for square-edged orifices, it seems reasonable to believe that for values of $\frac{D}{d}$ less than 1.5 there may be a slight advantage in using
the bevel-edged orifice, although the present experiments are not sufficiently comprehensive to confirm fully this belief.

The curves in Figs. 9 and 14 are of value as an indication of the importance of having the edges of the square-edged orifice sharp and square if the coefficients of discharge for square-edged orifices are expected to hold good. In permanent installations this will make it important that the orifice plate be of some material which does not rust or corrode easily.
V. Summary

25. General Applicability of Pipe Orifice Method.—The foregoing discussion has shown that the thin-plate orifice inserted in a pipe may be used with confidence for measuring the discharge of water through pipes. Like nearly all methods of measuring water it is subject to some limitations although it helps to fill a growing need which has been partly filled by the pitometer and by the injection of chemicals. The pipe orifice is in effect a portable Venturi meter, the disadvantage of the pipe orifice being the relatively large lost head caused by the obstruction of the orifice plate; however since the pipe orifice method is probably best adapted to temporary use the lost head may in general be unimportant. In a long pipe line also the lost head caused by the orifice would be relatively small. Cases in which the pipe orifice should be of particular value have already been suggested in the introduction.

Although all the deductions and conclusions given in this summary apply to the measurement of water, attention should be called to the fact that the pipe orifice is adapted to measuring the discharge of air, gas, and steam through pipes.

26. Conclusions.—The following points are important as a guide to the proper use of the pipe orifice method of measuring the discharge of water through a pipe:

(1) The two sections of the pipe between which change in pressure head may be most reliably determined are the section at which normal flow is discontinued and the stream begins to converge as it approaches the orifice and the section of greatest contraction of the jet after it leaves the orifice. Regardless of the size of pipe, for all sizes of orifice which it is feasible to use, the distance from the plane of the orifice to the section of beginning of convergence may be taken as eight-tenths the pipe diameter, and the distance to the section of greatest contraction as four-tenths the pipe diameter (section 11, p. 21).

(2) The drop in pressure head between these two sections is greater than that to be found for any other two sections near the orifice.
(3) Having given the measured difference between the pressure head at the section of beginning of convergence and the pressure head at the section of greatest contraction the discharge may be determined through the use of equation (2), p. 12, or through the use of equation (6), p. 35.

(4) The coefficient of discharge to be used in equation (2) is a variable quantity (Table 4, p. 30). It decreases as the size of pipe increases; it decreases slightly as the drop in pressure head increases; it has a minimum value for orifices having a diameter of one-third that of the pipe and increases as the diameter of the orifice becomes greater or becomes less than one-third the diameter of the pipe.

(5) The lost head caused by any given orifice in the pipe in terms of the velocity in the pipe may be determined by equation (3), p. 13.

(6) The lost head is always less than the drop in pressure head but approaches it in value as the ratio of the diameter of the pipe to the diameter of the orifice increases (section 6, p. 13).

(7) Due to the fluctuations of the liquid in the gage tubes the systematic error of reading the gage increases as the ratio of the diameter of the pipe to that of the orifice decreases, but when that ratio $\frac{D}{d}$ is 2 or greater the error may under normal conditions of flow be reduced to a negligible quantity by a proper manipulation of apparatus. As $\frac{D}{d}$ becomes less than 2 the accidental error of reading the gage increases very rapidly (section 19, p. 40) and also small errors in the measurement of the diameter of the pipe or the diameter of the orifice are likely to be the constant sources of an error of increasing magnitude in the computed discharge (section 14, p. 34). The indications are that, for favorable conditions of flow and with care in installing the apparatus and in observing, discharge may be determined generally within 2 per cent when the diameter of the orifice is not in excess of two-thirds that of the pipe, but this size of orifice seems to be about the maximum that can be used except for approximate determinations of discharge. When the magnitude of the lost head is not the controlling factor in the choice of size of orifice, best results
are likely to be obtained if the diameter of the orifice is not greater than one-half that of the pipe.

(8) For orifices having a diameter greater than one-half that of the pipe the use of two opposite pressure openings at each section is important because of the probability of the orifice being somewhat eccentric with the pipe, unless greater care is taken in placing the orifice than will usually be found practicable (sections 22, p. 44, and 23, p. 45). Systematic errors of observing may be greatly reduced by proper throttling (section 21, p. 43).

(9) The coefficient of discharge for bevel-edged orifices is a much more variable quantity and is materially greater than the coefficient of discharge for thin square-edged orifices. The use of the bevel-edged orifice seems not to be practicable, except for approximate measurements when the orifice diameter is greater than two-thirds of the pipe diameter (section 24, p. 46).
LIST OF PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION


Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. None available.


*A limited number of copies of bulletins starred are available for free distribution.


Bulletin No. 44. An Investigation of Built-up Columns under Load, by Arthur N. Talbot and Herbert F. Moore. 1911. Thirty-five cents.

*Bulletin No. 45. The Strength of Oxyacetylene Welds in Steel, by Herbert L. Whittemore. 1911. Thirty-five cents.


*Bulletin No. 55. Starting Currents of Transformers, with Special Reference to Transformers with Silicon Steel Cores, by Trygve D. Yensen. 1912. Twenty cents.


* A limited number of copies of bulletins starred is available for free distribution.


Bulletin No. 60. The Coking of Coal at Low Temperatures, with a Preliminary Study of the By-Products, by S. W. Parr and H. L. Olin. 1912. Twenty-five cents.


*Bulletin No. 64. Tests of Reinforced Concrete Buildings under Load, by Arthur N. Talbot and Willis A. Slater. 1913. Forty cents.


Bulletin No. 71. Tests of Bond between Concrete and Steel, by Duff A. Abrams. 1914. One dollar.


*A limited number of copies of bulletins starred is available for free distribution.


Bulletin No. 91. Subsidence Resulting from Mining, by L. E. Young and H. H. Stock. None available.


*Bulletin No. 95. The Embrittling Action of Sodium Hydroxide on Soft Steel, by S. W. Parr. 1917. Thirty cents.


Circular No. 4. The Economical Purchase and Use of Coal for Heating Homes, with Special Reference to Conditions in Illinois. 1917. Ten cents.


*Bulletin No. 100. Percentage of Extraction of Bituminous Coal with Special Reference to Illinois Conditions, by C. M. Young. 1917.


*Bulletin No. 106. Test of a Flat Slab Floor of the Western Newspaper Union Building, by Arthur N. Talbot and Harrison F. Gunnerman. 1918. Twenty cents.

Circular No. 8. The Economical Use of Coal in Railway Locomotives. 1918. Twenty cents.


*A limited number of copies of bulletins starred are available for free distribution.
THE UNIVERSITY OF ILLINOIS
THE STATE UNIVERSITY
Urbana
EDMUND J. JAMES, Ph. D., LL. D., President

THE UNIVERSITY INCLUDES THE FOLLOWING DEPARTMENTS:

The Graduate School

The College of Liberal Arts and Sciences (Ancient and Modern Languages and Literatures; History, Economics, Political Science, Sociology; Philosophy; Psychology, Education; Mathematics; Astronomy; Geology; Physics; Chemistry; Botany, Zoology, Entomology; Physiology; Art and Design)

The College of Commerce and Business Administration (General Business, Banking, Insurance, Accountancy, Railway Administration, Foreign Commerce; Courses for Commercial Teachers and Commercial and Civic Secretaries).

The College of Engineering (Architecture; Architectural, Ceramic, Civil, Electrical, Mechanical, Mining, Municipal and Sanitary, and Railway Engineering)

The College of Agriculture (Agronomy; Animal Husbandry; Dairy Husbandry; Horticulture and Landscape Gardening; Agricultural Extension; Teachers' Course; Household Science)

The College of Law (three-year and four-year curriculums based on two years and one year of college work respectively)

The College of Education

The Curriculum in Journalism

The Curriculums in Chemistry and Chemical Engineering

The School of Railway Engineering and Administration

The School of Music (four-year curriculum)

The School of Library Science (two-year curriculum for college graduates)

The College of Medicine (in Chicago)

The College of Dentistry (in Chicago)

The School of Pharmacy (in Chicago; Ph. G. and Ph. C. curriculums)

The Summer Session (eight weeks)

Experiment Stations and Scientific Bureaus; U. S. Agricultural Experiment Station; Engineering Experiment Station; State Laboratory of Natural History; State Entomologist's Office; Biological Experiment Station on Illinois River; State Water Survey; State Geological Survey; U. S. Bureau of Mines Experiment Station.

The library collections contain (March 1, 1919) 431,654 volumes and 53,858 pamphlets.

For catalogs and information address

THE REGISTRAR
Urbana, Illinois