ORIFICE COEFFICIENTS — DATA AND RESULTS OF TESTS

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This paper discusses the results of experimental work conducted at the Research Laboratory of the Republic Flow Meters Co., of Chicago, on the use of orifice plates for measuring the flow of fluids in pipes.

Extensive tests were carried on for a period of several years to determine the effect of the varying factors such as the orifice ratio, the size of the pipe, and the distance of the upstream and downstream connections upon the pressure difference across the orifice plate. The tests were conducted on seven sizes of pipes, from 2-in. to 12-in. standard. Fourteen orifice ratios were used in each size and twelve connections were tested on each side of the orifice plate.

The tests were made on the flow of atmospheric air, supplied by a Sturtevant blower having a maximum capacity of 6000 cu. ft. per min., at a pressure of 10 in. of water. The air passing through the orifice was measured by five calibrated impact tubes ranging from 1 in. to 4 in. in internal diameter. A detailed account is given of the calibration of the impact tubes, and curves were plotted showing the coefficient as a function of the impact head through the tube.

The arrangement of the installation for the final tests is described and illustrated in detail, and an account is given of the method of testing the various orifices. The theoretical relation of the functions is given briefly, preceded by elaborate definitions of the terms involved. The paper includes a number of tables and a collection of characteristic curves that may be employed for determining the flow through orifice plates in a given size of pipe.

I T HAS been long established in the literature of mechanical engineering, and especially in the various textbooks on hydraulics, that a stream of fluid issuing from a rounded aperture in the wall of a large vessel can be gaged accurately by the difference in static pressure between the inside and the outside of the vessel containing that fluid.

2   The relation between the pressure difference and the velocity

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of the jet issuing from the aperture has been derived theoretically for jets flowing into the open atmosphere and also for jets submerged under a lower head of the same fluid. It has been established by numerous experiments that upon leaving the vessel the cross-section of the stream is gradually reduced in area until, at a point known as the vena contracta, it is only about 60 per cent of the actual area of the aperture in the wall of the vessel. This contrivance used as a device for measuring the flow of fluids has been termed the "frictionless" or "thin-plate" orifice.

3   Recently the principle of the thin-plate orifice has been successfully applied to measuring the flow of fluids in pipes by the drop of pressure through the restricted area of an orifice plate placed between two flanges of the given pipe. At first the practice was limited entirely to cases where the area of the opening was much smaller than the cross-section of pipe, so that they could be considered as being similar to the submerged aperture in the wall of a large vessel. Further developments in this application have necessitated the use of larger-ratio orifices, which obviously differ from the case of the jet issuing from the large vessel, and therefore cannot be treated in the same manner. A comparison of the two cases with reference to Fig. 1 brings out the following points of difference:

4   First, in the case of the thin-plate orifice in the large vessel, the velocity of the jet issuing from the wall represents the equivalent of the hydrostatic head or pressure above the center of the opening, since the fluid in the vessel may be considered to be at rest. In the case of the pipe orifice it is the increase in velocity over the velocity of approach that is equivalent to the differential head across the orifice. This item may be termed the effect of initial velocity in the pipe.

5   Second, in the case of the pipe orifice the formation of the stream may be greatly affected by the proximity of the walls of the pipe both on entering and on leaving the orifice. In the case of the large vessel this effect is eliminated on either side of the orifice and the stream of the fluid can be freely formed into the natural contraction of the issuing jet. This item may be termed the effect of the size of the pipe or of the proximity of the walls.

6   Third, in the case of the large vessel the pressure difference affecting the flow of the fluid is fixed by the difference between the pressure inside and outside the vessel. In the case of the pipe orifice.it is necessary to obtain the pressure difference between a

point ahead of the orifice where the current is parallel to the walls
of the pipe, and a point beyond it where the jet has been fully con-
tracted, in order to have the true equivalent of the increased velocity
pressure of the jet. This may be termed the effect of shifting the
pressure taps on either side of the orifice.

7 These given points of difference are demonstrated graphi-
cally in Fig. 1 to show their relations to the dimensional quantities
involved. Thus, the effect of initial velocity is a function of the
relation between the velocity V of the fluid in the pipe and the
velocity v of the jet at the point of greatest contraction, or of the
ratio d^2/D^2 between the cross-sections, which, in its turn, is a func-
tion of the jet contraction X and of the ratio between the cross-
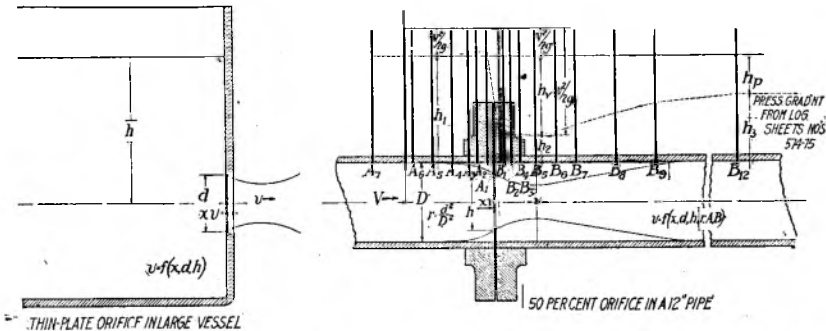

FIG. 1   THIN-PLATE ORIFICE — JET CONTRACTION AND PRESSURE GRADIENT

section of the orifice and the cross-section of the pipe. The effect
of restriction or the proximity of the walls is a function of the dis-
tance between the wall of the pipe and the edge of the opening,
which, in its turn, is a function of the diameter D of the pipe for
any given orifice ratio. The effect of shifting the pressure taps is
necessarily a function of the location of the taps on the A and B
sides of the orifice plane.

8 The experimental work described in the following para-
graphs was undertaken with the object of obtaining the necessary
data for this analysis: namely, to determine by actual tests the
effect produced in the pipe orifice, used as a flow-measuring device,
by the variation of the orifice ratio, by changing the size of the
pipe, and by shifting the pressure taps on either side of the orifice
plate.

9   In the early part of 1919 the engineering department of the Republic Flow Meters Company began its first series of orifice tests on several sizes of pipes.   It was realized at the start that an enormous number of comparative tests would be necessary to take care of all the variables involved.   The plan was laid out to test seven sizes of pipes, from 2-in. to 12-in. standard.   It was considered necessary to prepare fourteen orifice plates for each size, varying the orifice ratio from 5 to 70 per cent.   It was desired to make twenty-four pressure taps on each pipe, twelve on the upstream side and twelve on the downstream side of the orifice plates.   Ac-

FIG. 2   INTERIOR OF RESEARCH LABORATORY

cordingly, the number of tests involved would be seven for size of pipe, fourteen for orifice ratio, twelve for upstream distances, twelve for downstream distances, and, varying one condition at a time, would necessitate at least $7 \times 14 \times 12 \times 12$ or a total of 14,112 tests; and counting duplications and discarded tests, probably a total of 20,000 in all.   To make a reliable quantitative test with any kind of fluid — steam, water, air, or gas — it would require at least one hour for each condition at varying velocities, not counting preparations and adjustments.   Running constantly at the rate of six tests per day, three hundred days a year, it would require eleven years for the completion of the work.   It was obvious, therefore,

that a simplified method of testing was necessary in order to accomplish the work in a reasonable amount of time.

10   The idea was conceived at that time of laying out a system of testing whereby the variables involved could be determined for large-ratio orifices by comparison with the known or approved and tested value of the coefficient in small-ratio orifices, approaching the condition of the rounded aperture in the large vessel.   Immediately a trial installation was made on three sizes of pipes, 2-in., 4-in. and 6-in. standard, and for the basis of comparison two impact nozzles were prepared, one 1 in. in diameter and the other 2 in., and these were calibrated by a 10 per cent orifice in the 4-in. pipe.
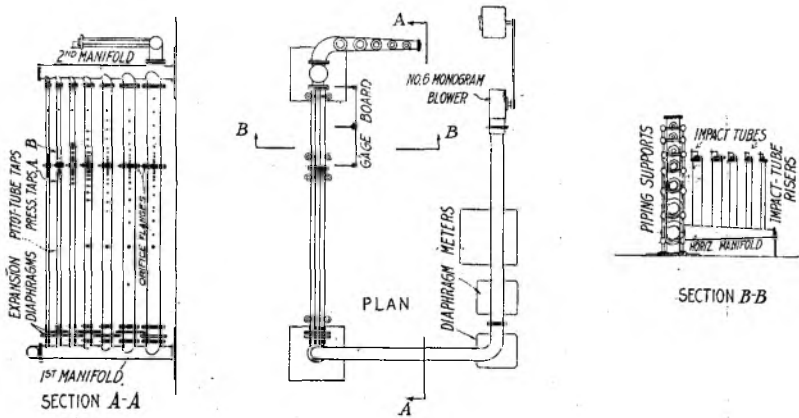

FIG. 3   GENERAL LAYOUT OF RESEARCH LABORATORY EQUIPMENT

11   The method of procedure was, first, to determine the coefficient of the impact tube by comparing it with the 10 per cent orifice in the 4-in. pipe.   The coefficient of the orifice at that ratio was taken arbitrarily to be 0.61, making some allowance for the initial velocity and the proximity of the walls of the pipe.   The method of testing involved merely the comparison of coefficients in either case, which could be done by taking a momentary reading of the gages for each test.

12   A number of major tests were performed on that installation and the results were plotted tentatively for comparison.   The curves obtained have demonstrated the importance of spacing properly the pressure taps on either side of the orifice plane by showing the general tendency of the coefficient of discharge to vary widely with the change of the taps, especially at the increased ratios

of orifice to pipe cross-section.   The results, however, were not considered as final, as the tests were intended merely to furnish a general outline of the subject for investigation, and extreme accuracy was not sought for in the computations.   From this outline plans were laid out for increasing the scope of the work to include larger sizes of pipes and also to establish more accurate standards of comparison.

THE FINAL INSTALLATION

13   On the removal of the company to its new headquarters in 1920, a research laboratory was established on the second floor of
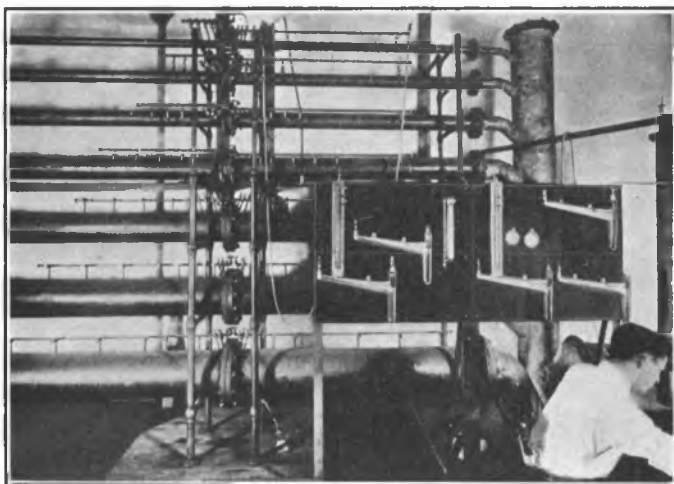
FIG. 4   PHOTOGRAPHIC VIEW OF FLANGES, PRESSURE TAPS AND GAGE BOARD

the factory building for the purpose of furthering the experimental work on orifice coefficients.   Fig. 2 is a view of this laboratory and Fig. 3 shows the general arrangement of apparatus as originally installed.

14   The installation comprises several parallel piping units ranging in size from 2-in. to 12-in. standard and terminating at the ends in two 12-in. vertical manifolds.   The second manifold opens into a horizontal outlet to which are attached five risers, each of which has an impact nozzle at the upper extremity.

15   The flow is produced by a No. 6 Sturtevant blower driven by a 15-hp. motor, and having a capacity of 6000 cu. ft. of air per

minute at a pressure of 10 in. of water. To vary the velocity of flow, an adjustable air gate was attached to regulate the intake to the blower.

16   Fig. 4 shows the extension of piping toward the second manifold and the impact nozzles. The flanges which support the orifice plates are shown with the pressure taps extending along the pipe on either side. The panel board in front of the piping supports the gages for measuring the various heads, a barometer, and a hygrometer. The vertical gages on the board were used only for heads of over 8 in. of water, which is above the range of the smaller extension type shown.
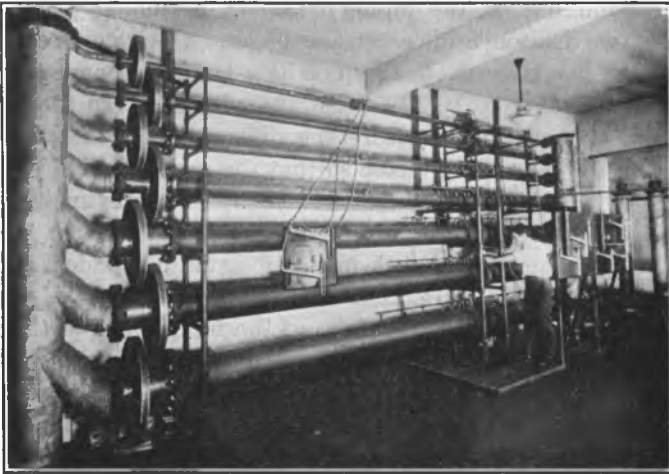
FIG. 5   PHOTOGRAPHIC VIEW SHOWING EXPANSION DIAPHRAGMS

17   The pressure taps are controlled by special needle valves and terminate in the horizontal pressure manifolds that extend along the pipe. These manifolds also end in needle valves to which may be attached the rubber tubing to connect to the gages.

18   Fig. 5 is a view of the piping from the first manifold toward the flanges. The enlarged sections shown between the manifold and the piping are expansion diaphragms which permit a lateral movement of 1 in. without straining the joints of the piping. This arrangement is necessary in order to allow sufficient separation of the flanges for inserting the orifice plates.

19   The length of straight piping in front of the orifice plate,

exclusive of the diaphragms and inlets, is 12 ft. and beyond the plate 6 ft., not counting the inlets to the second manifold. These lengths were necessary to insure a straight-line flow ahead of the orifice and a complete restoration beyond it.

20   It was still possible, however, that the air as it entered the tubes would have a tendency to rush to the bottom of the pipe since the inlets opened downward; that is, in the direction of the flow in the manifold. To prevent this the inlets were partitioned inside by a series of vanes so arranged that part of the air was caught at the top and along the sides of the pipe. This gave the even distribution of the flow through the pipe section necessary for standard conditions.

21   Mounted on the piping is shown a smaller panel board carrying two Ellison 8-in. extension gages. One was used to determine the line pressure in the pipe at a point far enough in front of the orifice plate to be free from the effects of the interceptive flow; and the other to measure the differential of the pitot tube inserted in the pipe being tested so that the work could also include a study of pitot-tube coefficients. The tests were made with a bevel-edged pitot tube in which the openings faced in opposite directions and the edge of each made an angle of 70 deg. with the direction of the flow.

22   Fig. 2 shows the five risers at the further end of the room. The top of each of these risers is fitted with a pair of flanges and the opening in the upper flange is tapped to receive the nozzle.

23   The impact nozzle proper is made of monel metal. It was designed according to the proportions given by Mr. Wm. L. De-Baufre in his paper on the calibration of nozzles [1] presented at the Annual Meeting of the Society in 1920. Fig. 6 is a sample design showing the dimensions of tube No. 2. .

24   Four sizes of openings are used and the nozzles are designated accordingly. No. 1 has an internal diameter of 1 in.; No. 2, of 2 in.; No. 3, of 3 in.; and Nos. 4 and 5 each with an internal diameter of 4 in.

25   To measure the velocity head of the air passing through the nozzle, $\frac{1}{4}$-in. bent tubes are used facing the flow and connected to the gages by rubber tubing, as in Fig. 6. These tubes are supported by means of a sliding seat fitted on a stem screwed into the side of the nozzle and can be adjusted vertically so that the dis-

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[1] Calibration of Nozzles for the Measurement of Air Flowing into a Vacuum, Trans. Am.Soc.M.E., vol. 42, p. 641.

tance from the opening of the tube to the outlet of the nozzle may be varied from nothing to several inches.

26   The pressure at the base of the risers leading to the impact tubes is also recorded. This static pressure generally agreed with the velocity pressure of the impact, differing somewhat at higher velocities by the small friction drop through the risers.

27   Table 1 gives the distances in inches from the plane of the orifice to the pressure taps. There are twelve of these taps on each side and thirteen on the downstream side for the smaller pipe sizes: seven placed closely together in the first diameter length, two in the second diameter length, and the remaining three at intervals of one
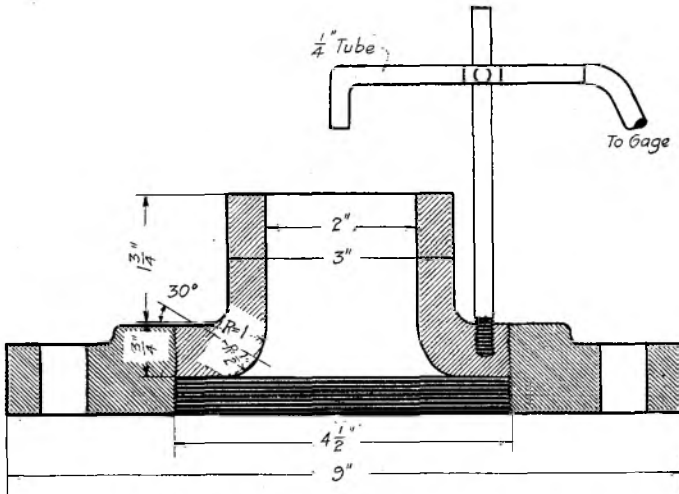
FIG. 6   SAMPLE DESIGN, IMPACT NOZZLE NO. 2

diameter length. These distances were chosen after preliminary tests had been made to set the points of possible variation of the differential pressure and also the limiting points of this variation.

28   Four thermometers are used to obtain the necessary temperature measurements. The first is placed in the first manifold and measures the temperature of the air as it comes to the pitot tube. The second is placed in the second manifold and gives the temperature of the flow in the line. The third is held over the opening of the impact nozzle, giving the temperature of the outcoming air. The fourth is on the board to measure the temperature of the ambient air.

29   The orifice plates were prepared from sheets of monel metal $\frac{1}{32}$ in. in thickness and were machined down to size to within a thousandth of an inch.   The form shown in Fig. 7 was adopted to insure proper centering of the orifice.   The two handles, placed

TABLE 1   DISTANCES IN INCHES FROM PLANE OF ORIFICE TO
UPSTREAM AND DOWNSTREAM PRESSURE TAPS

No.	Approx. Diam. Length	PIPE SIZES IN INCHES						
		2	3	4	6	8	10	12
					Upstream (A) Taps			
1	0.05	0.28	0.28	0.44	0.52	0.66	0.66	0.88
2	0.10	0.38	0.34	0.59	0.61	0.86	1.00	1.17
3	0.20	0.41	0.66	0.72	1.11	1.46	2.08	2.45
4	0.30	0.59	0.94	1.28	1.83	2.44	3.00	3.70
5	0.50	1.00	1.47	2.00	3.05	4.08	5.03	6.09
6	0.75	1.53	2.28	2.97	4.58	6.08	7.48	9.11
7	1.00	2.03	3.00	3.93	6.07	8.14	10.06	12.11
8	1.50	3.03	4.56	5.96	9.14	12.16	15.05	18.17
9	2.00	4.10	6.15	7.96	12.14	16.22	20.12	24.09
10	3.00	6.20	9.15	12.02	18.24	24.35	30.25	36.33
11	4.00	8.20	12.15	16.02	24.34	32.48	40.38	48.38
12	5.00	10.20	15.25	20.08	30.44	40.58	50.45	60.50
					Downstream (B) Taps			
1	0.05	0.25	0.25	0.45	0.50	0.68	0.80	0.59
2	0.10	0.34	0.34	0.56	0.71	0.82	1.03	1.18
3	0.20	0.41	0.66	0.59	1.14	1.43	2.00	2.36
4	0.30	0.53	0.91	1.28	1.75	2.44	3.02	3.60
5	0.50	1.00	1.56	1.98	3.05	4.07	5.08	6.02
6	0.75	1.53	2.28	2.91	4.58	6.13	7.58	9.08
7	1.00	2.09	3.09	3.91	6.07	8.18	10.08	12.11
8	1.50	3.09	4.62	5.89	9.08	12.24	15.16	18.15
9	2.00	4.09	6.16	7.92	12.13	16.29	20.22	24.18
10	3.00	6.14	9.22	11.94	18.22	24.43	30.38	36.43
11	4.00	8.17	12.27	16.00	24.29	32.58	40.47	48.52
12	5.00	10.25	15.36	20.03	30.36	40.69	50.59	60.74
13	...	48.50	48.50	48.50	48.50	48.50	...	...

90 deg. apart, support guide pins so located that they will rest on two filed points on the flanges when the orifice is properly placed in the pipe.   The figure also shows the method of centering and the measurements necessary.

METHOD OF TESTING

30 There are three classes of preparations to be considered before starting the test proper. They are as follows:

    a The preparations for any one of the runs made on an orifice already installed, which are (1) the selection of standards, and (2) checking of the gages

    b Preparations for a complete test of any given orifice, which include the preparation of the plate, besides the steps given under (*a*)
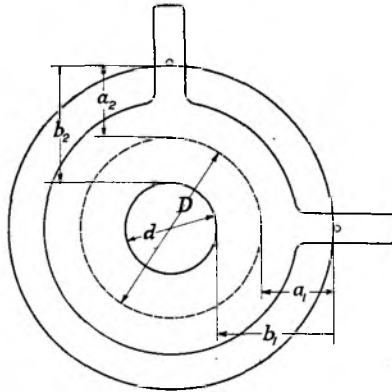

FIG. 7 METHOD OF CENTERING ORIFICES IN FLANGES

$a_1 + 0.5D = b_1 + 0.5d$ = distance to center of pipe; also $a_2 + 0.5D = b_2 + 0.5d$ = distance to center of pipe; hence $b_1 = a_1 + 0.5 (D - d)$ and $b_2 = a_2 + 0.5 (D - d)$. (d = orifice diameter; D = inside pipe diameter; a_1 and a_2 = radial distances from inside of pipe to point outside of flange; b_1 and b_2 = distances from orifice diameter to pins on handles.)

    c The preparations for a set of tests on any given pipe which include (1) the examination of the pipe and flanges, (2) testing of the valves and connections, and also the steps in (*a*) and (*b*).

31 The complete work is actually carried on in the following way:

32 First, the pipe is spread apart at the flange and the inside wall thoroughly examined to make certain that there are no burrs on any one of the pressure openings and that the ends of the brass tubes are flush with the wall.

33 Two points are selected on the outside of the flange at

90 deg. apart and filed down to a measured radius in order to act as guides to secure proper centering of the orifice.

34   Second, the orifice to be tested is then selected and the edge of the opening examined carefully for burrs or chips.   Any

TABLE 2   SIZES OF PIPES AND ORIFICES

Orifice Diam. d	Orifice Ratio d^2/D^2	Orifice Diam. d	Orifice Ratio d^2/D^2	Orifice Diam. d	Orifice Ratio d^2/D^2
12-in. Pipe, $D = 12.08$ in.		10-in. Pipe, $D = 10.12$ in.		8-in. Pipe, $D = 8.12$ in.	
2.707	0.0505	2.264	0.0500	1.809	0.0496
3.825	0.1002	3.190	0.0993	2.572	0.1033
4.699	0.1516	3.934	0.1510	3.158	0.1500
5.430	0.2012	4.529	0.2002	3.632	0.2000
6.050	0.2504	5.062	0.2502	4.017	0.2447
6.620	0.3000	5.539	0.2996	4.456	0.3011
7.120	0.3496	5.961	0.3470	4.780	0.3465
7.635	0.3995	6.400	0.4000	5.140	0.4000
8.108	0.4507	6.770	0.4475	5.452	0.4508
8.530	0.4992	7.153	0.4996	5.752	0.5018
8.930	0.5465	7.500	0.5491	6.021	0.5498
9.392	0.6045	7.826	0.5980	6.279	0.5979
9.800	0.6580	8.193	0.6528	6.588	0.6583
10.093	0.6895	8.424	0.6930	6.781	0.6974
6-in. Pipe, $D = 6.06$ in.		4-in. Pipe, $D = 4.04$ in.		3-in. Pipe, $D = 3.06$ in.	
1.360	0.0504	0.908	0.0505	0.686	0.0500
1.918	0.1002	1.277	0.1000	0.968	0.1000
2.374	0.1534	1.568	0.1506	1.191	0.1516
2.724	0.2025	1.814	0.2016	1.372	0.2010
3.030	0.2500	2.012	0.2480	1.530	0.2500
3.336	0.3030	2.228	0.3041	1.666	0.3070
3.577	0.3484	2.389	0.3497	1.818	0.3530
3.838	0.4011	2.547	0.3975	1.939	0.4015
4.090	0.4533	2.704	0.4480	2.042	0.4453
4.280	0.4994	2.857	0.5000	2.155	0.4960
4.500	0.5520	2.992	0.5485	2.256	0.5435
4.680	0.5980	3.117	0.5952	2.368	0.5988
4.903	0.6490	3.257	0.6500	2.485	0.6595
5.070	0.7000	3.385	0.7015	2.562	0.7010

roughness or dirt found on the edge is carefully removed without changing the size of the opening in any way.

35   The average diameter is then accurately determined to 0.001 in. with a vernier scale and recorded on the log sheet.   The dimensions of the orifices for the various pipe sizes are given in Table 2.   The distance b from the edge of the orifice to the guide

pin must be carefully measured and checked by the formulas given in Fig. 7, a in the formula being the radial distance from the inside of the pipe to the filed marks on the flange.

36 The orifice is then inserted in the pipe between two gaskets so that the two pins fall on the filed marks and all connections are made airtight.

37 Third, the gages used are of the Ellison 8-in. extension type. They must be checked for zero reading and proper leveling before any test is made. The rubber tubing is shellacked at all connections to cut down possibility of error.

38 Fourth, all the impact nozzles and all the gages are then sealed off with the exception of the differential gages across the orifice. The blower is started and allowed to build up its maximum head in the pipes. The valves are then tested for leakage in the following manner:

39 There are two sets of valves, those on the upstream side of the orifice being known as A-valves, numbered from 1 to 12, according to the tap which they control; and those on the downstream side or B-valves, numbered in like manner from 1 to 13. Valves A_1 and B_1 are opened and the gage reading noted. If either valve leaks to the atmosphere there will be a slight flow in the valve and, consequently, a reduced pressure on the differential column. If a zero reading is shown there is no leakage, or at most it is negligible. Then A_1 is left open, B_1 closed, and B_2, B_3, B_4, etc., opened and tested in like manner. Then all the A-valves are tested in the same way. If no suction or pressure is shown on the gage for any of the connections, the valves are airtight. If any leak was shown it was remedied by either tightening or replacing the stuffing box.

40 Fifth, the proper standards must now be selected. There are five impact nozzles to choose from, which vary in size from No. 1, which is 1 in. in diameter, to Nos. 4 and 5, which are 4 in. in diameter. The proper one to select is the one having as nearly as possible the same area as the orifice being tested. Since the flows through the impact nozzle and orifice are identical, the velocities through these sections will be the same. The head on the impact nozzle will therefore be close to that across the orifice, being somewhat different, of course, due to the difference in the discharge coefficients.

41 If the orifice is very large, two or more nozzles may be necessary. In this case the sum of the nozzle areas should equal the orifice area approximately. Equating the squares of the diameters serves the same end and is simpler than finding the area.

42   When the proper nozzle has been selected, the impact tube leading to the gage is adjusted to the proper distance from the nozzle opening and centered accurately with respect to this opening.   From previous tests the proper distance to place the tube was found to be one-quarter of the nozzle diameter above the opening.   For tube No. 1. a distance of $\frac{1}{2}$ in. is used, since to approach the opening would, in this case, have the effect of reducing the area of the opening and, consequently, of changing the coefficient.

43   Sixth, the blower is started with the gate wide open to determine the maximum head that could be obtained for the given orifice plate.   This head is divided roughly into three or four steps to select the velocities at which the runs will be made.   The blower intake is then reduced until the head on the impact-tube gage is reduced to the lowest velocity selected.   The blower is allowed to run for a few minutes at this velocity before starting to take readings·

44   Seventh, valves A_1 and B_1 are then opened and the differential noted on the gage. B_2, B_3, etc., are opened successively until the highest differential is reached, indicating the position of the vena contracta in the flow.   The readings at this point are recorded on the log sheet.   Similar readings are taken for all the upstream taps, completing an A-run of the test.   The impact pressure is recorded only once during each run, since it is kept constant by adjusting the intake gate to the blower.   Temperature readings at the points previously mentioned are taken several times during each run.   The barometer and hygrometer readings are taken and recorded for each run.

45   Eighth, three B-runs are then made at the same velocity, with the upstream taps at 7, 8 and 9, which were found always to give the same lowest static pressure on the upstream side, indicating the section of uniform flow in the pipe.

46   Ninth, another A-run is then made at the same velocity, with the downstream tap at B_{12}, which was found to give the highest static pressure on the downstream side, indicating the section of complete restoration of pressure in the line.

47   The other velocity steps are repeated in the same manner, thus completing a test on a given-ratio orifice.

CALIBRATION OF IMPACT NOZZLES

48   At the outset of the tests an attempt was made to calibrate the impact tubes, one at a time, by a number of diaphragm displacement meters.   Three large meters, marked A, B, and C,

having a total capacity of 1000 cu. ft. per min., were connected to-
gether in such a manner that they could be run either in parallel or
in series with each other and the system of piping leading to the
impact nozzles.

49 A large number of tests (recorded in log sheets 1 to 199)
have given fairly uniform results at the lowest capacity of the
diaphragm meters, that is, at lower capacities the registration of
the diaphragm meters indicated the same coefficient for a 10 per
cent orifice in the 12-in. pipe and for the given impact nozzles,
whether one, two, or three of these meters were used. At higher
capacities the results varied greatly as compared with the flow indi-
cations. According to those results the coefficients of the impact
nozzles were shown to decrease as the velocity through the tube
increased, while from consideration of the effect of friction on the
flow in the nozzle, it would appear that the coefficient should rather
increase with increased velocity.

50 To verify the accuracy of the diaphragm meters a series
of tests was made, placing meters A, B, and C in series with each
other (log sheets 124 to 142) and then placing meters A and B in
parallel against C in series at various capacities (log sheets 152 and
153). The results obtained showed a greater variation in the com-
parative registration of the meters than was permissible for their
adoption as the standard of measurement.

51 From the data of these tests, when running the diaphragm
meters at low capacities the indications corresponded very closely
to the 10 per cent orifice in the 12-in. pipe, assuming the orifice
coefficient to be 0.61. It was decided, therefore, to recalibrate the
impact tubes against the 10 per cent orifice in the 12-in. pipe.

52 In calibrating each tube the method of procedure was
first to determine the setting of the tubes on the impact nozzle at
the flat part of the pressure curve, that is, at such a distance from
the face of the nozzle that a small variation in the distance would
not vary the reading of the gage for a given velocity of the air through
the tube. It was found that the flat part was reached at one-quarter
diameter from the face, with the exception of the 1-in. nozzle, where a
½-in. minimum was required for this purpose. When the tube was
placed at the proper setting, numerous runs were made at various
velocities, the data were recorded on the log sheets properly indexed
and filed, and the computations were made according to the standard
method adopted for the test; that is, the quantity of air in pounds
per minute was computed accurately for the orifice and for the im-

pact tubes, and the ratio of the two was recorded as the coefficient of the impact tube. Table 3 shows a sample test on impact tube No. 5 against the 10 per cent orifice in the 12-in. pipe, and Table 4 shows a similar test on the same tube with two orifices used for measuring the air.

TABLE 3   IMPACT-TUBE TEST

Log Sheet No. 1136. Tube No. 5: diameter, 4.004 in., $d^2 = 16.032$; setting, 1 in. Barometer, 29.62 in.; inches of water (p_o), 403; humidity per cent, 75; speed, 1800 r.p.m. Orifice standard, 10 per cent in 12-in. pipe; $K_n = 53.548$ for taps $A6$, $A7$, $B6$ and $B7$. Date, 5-24-22. Observers, A.F S & J.T.

No.	Pressures			Temperatures			Coefficients		
	Static h_s	12-in. Pipe h_n	Impact h_o	Impact t_1	Mani-fold t_m	Line t_b	G_o	G_n	C_o
1	0.14	0.590	0.200	75	76	79	11.13	11.63	0.957
2	0.21	0.895	0.305	..	..	..	13.72	14.36	0.956
3	0.27	1.160	0.395	..	..	..	15.61	16.35	0.955
4	0.34	1.495	0.505	76	77	80	17.74	18.49	0.960
5	0 41	1.760	0.595	..	..	..	19.24	20.10	0.957
6	0.48	2.080	0.700	..	..	..	20.90	21.75	0.961
7	0.55	2.380	0.800	76	77	80	22.37	28.23	0.961
8	0.63	2.690	0.905	77	78	81	23.80	24.73	0.962
9	0.70	2.970	1.000	..	..	..	24.97	26.00	0.961
10	0.77	3.290	1.100	..	..	..	26 30	27.30	0.963
11	0.84	3.600	1.200	77	78	81	27.50	28.50	0.965
12	0.91	3.890	1.300	78	79	81	28.60	29.70	0.963
13	0.98	4.220	1.400	..	..	..	29.80	30 80	0.967
14	1.05	4.490	1.500	..	..	..	30.70	31.85	0.964
15	1 12	4.830	1.600	78	79	81	31.85	32.90	0.968
16	1 19	5.090	1.700	..	..	..	32.70	33.77	0.968
17	1 26	5.380	1.795	..	..	..	33.60	34.70	0.968
18	1.33	5.700	1.900	78	79	81	34.60	35.70	0.969
19	1.40	6.010	2.000	..	..	..	35.60	36.60	0.973
20	1.47	6.310	2.100	79	80	82	36.40	37.54	0.969
21	1.54	6.620	2.200	..	..	..	37.30	38.40	0.972
22	1.62	6.910	2.300	..	..	..	38.10	39.30	0.970
23	1.69	7.200	2.400	79	80	82	38.90	40.10	0.970
24	1.76	7.520	2.500	..	..	..	39.80	40.90	0.973

IMPACT-TUBE COEFFICIENTS

53   The impact-tube coefficients as obtained in the final calibration are given in Figs. 8, 10, 11, 12, and 13, for tubes Nos. 1, 2, 3, 4 and 5.   The points of calibration are reproduced on each curve to show the limits of accuracy in the observations.   It will be noticed that while there is a considerable difference — as high as 1 per cent — in the actual value of the coefficient for the various sizes of tubes, all

five curves show the same characteristic of sloping downward at the reduced impact pressure. The same shape of curve was obtained when plotting the results on the basis of orifice differential when the tests were limited to one tube and one orifice. The question naturally arose whether this characteristic was due to the tendency of the impact-tube coefficient to increase with increased head, or of the orifice coefficient to decrease with increased head.

TABLE 4 IMPACT-TUBE TEST

Log Sheet No. 1137. Tube No. 5: Diameter, 4.004 in.; $d^2 = 16\,032$; setting, 1 in. Barometer, 29.53 in.; inches of water (p_0), 401.6; humidity per cent, 75; speed, 1800 r.p.m. Orifice standard 10 per cent in 12-in. pipe: $K_n = 53.548$ for taps $A7$, $B6$; orifice standard 10 per cent in 10-in. pipe; $K_n = 37.183$ for taps $A7$, $B6$. Date, 5–24–22. Observers, A.F.S. & J.T.

No.	Pressures				Temperatures			Coefficients		
	Static h_s	12-in. Pipe h_n	10-in.Pipe h_n	Impact h_o	Impact t_1	Mani-fold t_m	Line t_b	G_o	G_n	C_o
1	0.28	0.305	0.310	0.300	75	76	79	13.56	14.22	0.954
2	0.45	0.505	0.515	0.495	....	....	....	17.47	18.26	0.957
3	0.66	0.725	0.740	0.700	75.5	76.5	80	20.93	21.70	0.964
4	0.84	0.930	0.950	0.900	....	....	....	23.71	24.60	0.964
5	1.03	1.140	1.165	1.100	....	....	....	26.24	27.20	0.965
6	1.25	1.345	1.385	1.300	76.5	77.5	80.5	28.57	29.60	0.965
7	1.41	1.550	1.590	1.500	....	....	....	30.69	31.80	0.965
8	1.59	1.755	1.790	1.700	....	....	....	32.45	33.80	0.961
9	1.79	1.975	2.010	1.900	77	78	80.5	34.65	35.80	0.968
10	1.98	2.195	2.225	2.100	....	....	....	36.38	37.60	0.968
11	2.18	2.405	2.440	2.300	....	....	....	38.08	39.40	0.967
12	2.37	2.615	2.650	2.500	77	78	80.5	39.71	41.00	0.969
13	2.57	2.860	2.875	2.700	....	....	....	41.50	42.70	0.972
14	3.16	3.49	3.52	3.30	....	....	....	45.83	47.10	0.973
15	3.44	3.82	3.83	3.60	77	78	80.5	47.88	49.30	0.971
16	3.83	4.23	4.26	4.00	....	....	....	50.60	51.90	0.975
17	4.19	4.65	4.68	4.40	....	....	....	53.10	54.40	0.976
18	4.28	4.63	4.68	4.40	76	77	80	53.00	54.30	0.976
19	4.60	5.04	5.09	4.80	....	....	....	55.20	56.80	0.973
20	4.93	5.45	5.50	5.20	....	....	....	57.50	59.10	0.974
21	5.32	5.88	5.92	5.60	77	78	81	59.80	61.30	0.976
22	5.70	6.29	6.34	6.00	....	....	....	61.70	63.40	0.974

54   To determine this question, a number of similar tests were made with two orifice plates in parallel against one impact tube (see Table 4), thereby changing the relation between the impact head and the orifice differential for the same amount of flow. Fig. 9 shows the results of the tests on the No. 5 tube plotted on the basis of orifice differential, which are a reproduction of the same tests shown in Fig. 8 on the basis of impact head. It will be
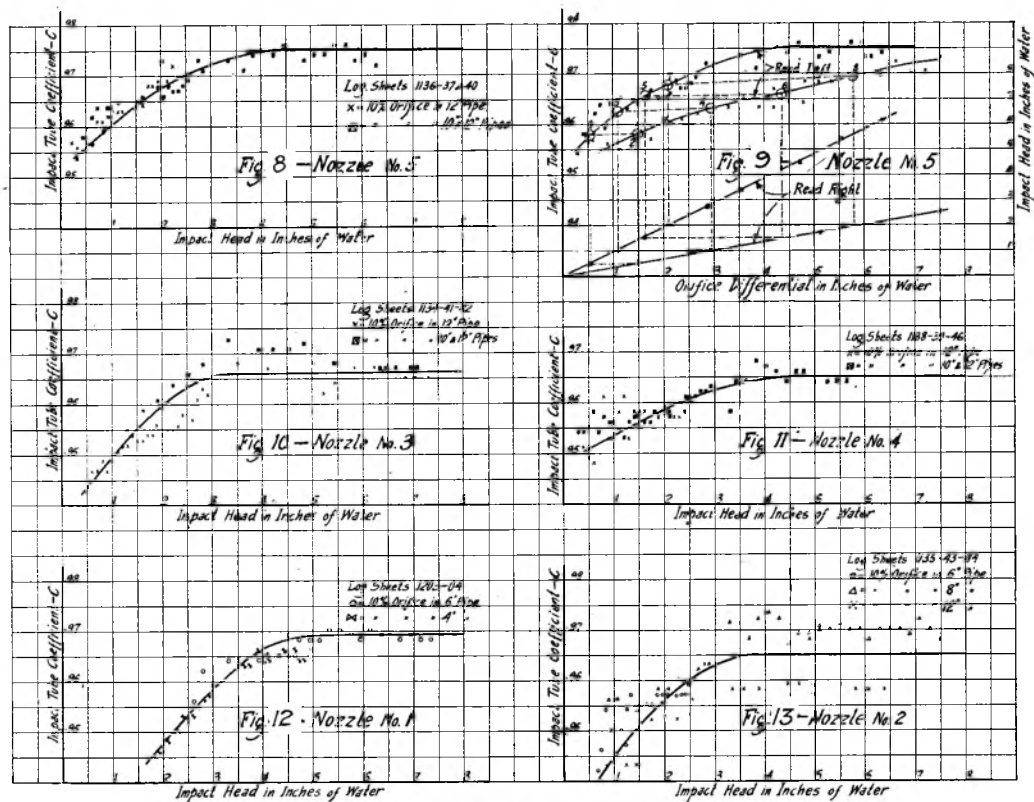
FIGS. 8 TO 13   IMPACT-TUBE COEFFICIENTS

observed that while in Fig. 8 all the points of the tests are covered by one curve, those in Fig. 9 require two curves, following the difference in the impact head.

55   To demonstrate the case two other curves were drawn on the same chart, showing the impact head corresponding to each test. By tracing the points marked on the curves it will be noticed that the same coefficient is obtained for the same impact head regardless of the difference in the orifice head, thus demonstrating the fact that the variation in the coefficient is due to the effect of the change in velocity through the impact nozzle. This can be explained by the fact that the coefficient of friction increases considerably at very low velocities, which accounts for the reduced amount of flow through the impact nozzle.

56   The question further arose regarding the difference in the coefficients of the various tubes. At first an attempt was made to explain the difference by the possible error in the measurement of the diameter of the impact tube. This, however, could not be the case, as the vernier can be read easily within a thousandth of an inch, which, in the case of the Nos. 4 and 5 tubes, would make the error entirely insignificant. Numerous tests were repeated for the purpose of ascertaining these discrepancies, and in every case there was shown to be a difference of about 1 per cent between the coefficients on the Nos. 4 and 5 tubes, both having the same internal diameter of approximately 4 in.

57   From the viewpoint of approach the No. 4 tube is farther away from the bend of the manifold than the No. 5 tube. When the two of them were open together, No. 4 would show a higher differential than No. 5, from which it appears that the shape of the approach to the tube has some effect upon the coefficient of discharge. To eliminate this effect it would appear that the approach to the impact tube should be made of larger relative size and at a longer distance from an elbow or bend in the pipe.

THEORETICAL RELATION OF FUNCTIONS

58   The following notation is adopted with reference to Fig. 1, in which most of the quantities and dimensions are demonstrated diagrammatically.

d = diameter of the thin-plate orifice, either in the restricted pipe or in the wall of the large vessel

D = diameter of pipe

X = percentage of jet contraction at the smallest cross-section or the vena contracta of stream. (Shown as x in Figs. 1, 14 and 15.)

r = ratio of orifice cross-section to pipe cross-section, or d^2/D^2; Xr = ratio of vena contracta to cross-section of pipe

$\rho = 1/r$ = ratio of pipe cross-section to orifice cross-section or D^2/d^2; ρ/X = ratio of pipe cross-section to the vena contracta of stream

A = distance from plane of orifice to upstream pressure taps

B = distance from plane of orifice to downstream pressure taps

h_1 = static pressure at section of normal flow ahead of orifice

h_2 = static pressure at section of vena contracta

h_3 = static pressure at section of normal flow beyond orifice

h = differential head between any two points on opposite sides of the orifice

h_v = differential head between the two points designated as h_1 and h_2. This quantity represents the pressure drop across the orifice corresponding to the increased velocity of the flow

h_p = differential head between the two points designated as h_1 and h_3. This quantity measures the total loss of pressure caused by the sudden contraction and expansion of the flow through the orifice

Z = ratio of h_p to h_v

V = velocity of fluid at section of normal flow in pipe

v = velocity of fluid at vena contracta of stream

Xv = velocity of fluid at section of orifice

Q = rate of flow or amount of fluid passing through the orifice in a given unit of time

C = coefficient of discharge defined by —

$$Q = C \frac{\pi}{4} \frac{d^2}{\sqrt{1-r^2}} \sqrt{2gh} = C \frac{\pi}{4} \frac{D^2}{\sqrt{\rho^2-1}} \sqrt{2gh}$$

C' = velocity coefficient of orifice defined by —

$$v = C' \sqrt{2gh}, \text{ and } C' = f(A)f(B)\sqrt{\frac{1}{1-X^2r^2}}$$

(XC') = orifice coefficient defined by —

$$Q = (XC') \frac{\pi}{4} d^2 \sqrt{2gh}$$

C'' = orifice coefficient defined by —

$$Q = C'' \frac{\pi}{4} D^2 \sqrt{2gh}, \text{ or } C'' = (XC')r$$

59   Subscript v, with reference to the given terms, applies to the condition of pressure tap A at normal flow ahead of the orifice plane and pressure tap B at the vena contracta. Subscript p applies to the condition of pressure tap A at normal flow ahead of the orifice plane, and pressure tap B at normal flow after the orifice plane.

60   In the case of the frictionless orifice in the large vessel the amount of fluid Q passing through the opening in a unit of

time is a function of the three variables: h, the differential head; d, the diameter of the opening; and X, the contraction of the jet upon leaving the vessel, or —

$$Q = f(X, d, h) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [1]$$

61   In the case of the pipe orifice, the rate of flow Q is a function of six variables: namely, the differential head h, the diameter of the orifice d, the jet contraction X, the orifice ratio r, and the high- and low-pressure distances A and B, respectively, or —

$$Q = f(X, d, h, r, A, B) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [2]$$

For the first case we may write the fundamental equation —

$$\frac{v^2}{2g} = h, \text{ or } v = \sqrt{2gh}$$

and

$$Q = \frac{\pi}{4} X d^2 v = \frac{\pi}{4} X d^2 \sqrt{2gh} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [3]$$

62   Equation [3] offers the complete development of Equation [1]. In this case X is the ratio of the actual amount of fluid passing through the jet and the theoretical amount corresponding to the differential head and the given size of the opening. If we assume a given test for determining this ratio, we obtain from the test the actual value of Q and the known values of d and h, so that—

$$X = \frac{Q}{\frac{\pi}{4} d^2 \sqrt{2gh}} = \text{coefficient of discharge} \quad . \quad . \quad . \quad . \quad . \quad [4]$$

63   For the case of the pipe orifice, the fundamental equation will refer primarily to the velocities V and v, and the corresponding heads h_1 and h_2, taking the form of —

$$\frac{V^2}{2g} + h_1 = \frac{v^2}{2g} + h_2$$

or —

$$\frac{v^2 - V^2}{2g} = h_1 - h_2 = h_v \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [5]$$

and since —

$$D^2 V = X d^2 v$$

therefore —

$$V = X \frac{d^2}{D^2} v = Xrv$$

Substituting in [5],

$$(1 - X^2 r^2) \frac{v^2}{2g} = h_v$$

or —

$$v = \sqrt{\frac{1}{1 - X^2 r^2}} \ \sqrt{2gh_v}$$

and —

$$Q = \frac{\pi}{4} X d^2 v = \frac{\pi}{4} X d^2 \sqrt{\frac{1}{1 - X^2 r^2}} \ \sqrt{2gh_v} \ \ . \ \ . \ \ . \ \ . \ \ [6]$$

64   Equation [6] offers the development of the functional expression [2] only with respect to the variables X, d, h, and r at the particular sections at which h_v is obtained. To make the equation general, we introduce $f(A)$ and $f(B)$ to take care of the effect of varying the location of the taps, so that, for any value of h,

$$Q = f(A) f(B) \frac{\pi}{4} X d^2 \sqrt{\frac{1}{1 - X^2 r^2}} \ \sqrt{2gh} \ \ . \ \ . \ \ . \ \ . \ \ [7]$$

where $f(A)$ and $f(B)$ are equal to unity when h_v is substituted for h.

65   If we now assume a given test for the purpose of determining the experimental functions of Equation [7], we obtain, on one hand, the value of Q, and on the other hand, the given values of d, h, and r, so that —

$$f(A) f(B) X \sqrt{\frac{1}{1 - X^2 r^2}} = \frac{Q}{\frac{\pi}{4} d^2 \sqrt{2gh}} \ \ . \ \ . \ \ . \ \ . \ \ [8]$$

or —

$$(XC') = \frac{Q}{\frac{\pi}{4} d^2 \sqrt{2gh}} \ \ . \ \ . \ \ . \ \ . \ \ . \ \ . \ \ [9]$$

where —

$$(XC') = X f(A) f(B) \sqrt{\frac{1}{1 - X^2 r^2}} \ \ . \ \ . \ \ . \ \ . \ \ [9a]$$

and —

$$Q = (XC') \frac{\pi}{4} d^2 \sqrt{2gh} \ \ . \ \ . \ \ . \ \ . \ \ . \ \ . \ \ [10]$$

66   That is, in the case of the pipe orifice, the experimental coefficient XC' is a function of the jet contraction X, the orifice ratio r, and the high- and low-pressure distances A and B, respectively. This function necessarily approaches unity as a limit when the conditions of the pipe orifice approach the condition of the rounded opening in a large vessel.

67   Equation [7] is often replaced by the form generally used for the venturi tube:

$$Q = C \frac{\pi}{4} \frac{d^2}{\sqrt{1 - r^2}} \ \sqrt{2gh} = C \frac{\pi}{d} \frac{D^2}{\sqrt{\rho^2 - 1}} \ \sqrt{2gh} \ \ . \ \ . \ \ [11]$$

68   The quantity C in Equation [11] is the coefficient of discharge for the orifice as compared with the coefficient of discharge for the venturi tube. In using this coefficient, it is always necessary when solving Equation [11] to compute the radical $\sqrt{1-r^2}$ for the given orifice ratio. This is especially troublesome when a solution is sought for the size of the orifice necessary for a given differential and amount of flow, as it involves two unknown quantities C and r. To overcome this difficulty, a modification of Equation [10] is employed with reference to the cross-section of the pipe. Since $d^2 = D^2 r$, we can write —

$$Q = (XC')r\, \frac{\pi}{4}\, D^2\, \sqrt{2gh}$$

or —

$$Q = C'' \frac{\pi}{4}\, D^2\, \sqrt{2gh} \quad . \quad . \quad . \quad . \quad . \quad . \quad \textbf{[11a]}$$

Equation [11a] in combination with a $C'' - r$ curve gives a direct solution for the size of orifice necessary for a given flow.

69   The pressures h_1, h_2, and h_3 at the three main sections of the orifice region are significant for the fact that they indicate the relation between the drop of pressure h_v equivalent to the increase in velocity and the pressure loss h_p, caused by the sudden contraction and expansion of the flow. From the above equations, we can write —

$$C_p\, \sqrt{h_p} = C_v\, \sqrt{h_v}$$

from which —

$$\text{Fraction of loss } Z = \frac{h_p}{h_v} = \left(\frac{C_v}{C_p}\right)^2 \quad . \quad . \quad . \quad . \quad \textbf{[12]}$$

and fraction of pressure restoration $= 1 - Z = 1 - \dfrac{h_p}{h_v} = 1 - \left(\dfrac{C_v}{C_p}\right)^2$.

The same applies to any of the experimental coefficients determined for the two sections corresponding to h_2 and h_3, respectively.

70   In calculating the data of a given test it is more convenient to obtain the quantity XC' directly as given in Equation [9] without any reference to the orifice ratio. Having obtained this quantity, the other functions can be easily computed from the known relations to XC'.

71   From the above equations we derive the values of X, C, and C'' in term of XC' as follows:

$$(XC') = X\, f\,(A)\, f\,(B)\, \sqrt{\frac{1}{1 - X^2 r^2}} \quad . \quad . \quad . \quad . \quad \textbf{[9a]}$$

Solving for X,

$$X = \frac{(XC')}{\sqrt{\{f(A)\,f(B)\}^2 + (XC')^2\,r^2}} \quad \cdots \quad [13]$$

At the vena contracta $f(A)\,f(B) = 1$. Therefore —

$$X = \frac{(XC')_v}{\sqrt{1 + (XC')_v^2\,r^2}} \quad \cdots \cdots \cdots \quad [13a]$$

Combining Equations [10] and [11],

$$(XC') = \frac{C}{\sqrt{1 - r^2}}$$

or —

$$C = (XC')\sqrt{1 - r^2} \quad \cdots \cdots \cdots \quad [14]$$

From Equations [10] and [11a],

$$(XC')\,d^2 = C''D^2$$

from which —

$$C'' = (XC')\frac{d^2}{D^2} = (XC')r \quad \cdots \cdots \cdots \quad [15]$$

COMPUTATION OF RESULTS

72   The method adopted was to compute the rate of flow in pounds per minute for the calibrated impact nozzles used as a standard, and the rate in pounds per minute derived theoretically for the given orifice plate, assuming XC' to be equal to unity. The actual value of the coefficient XC' for the given orifice is necessarily the ratio of the former to the latter. The method of procedure is demonstrated on the sample log sheets (Tables 5 and 6) which contain the data of one A-run and one B-run on the 12-in. pipe. The symbols designating the data and results on the log sheets refer to the following notation:

Pressure in Inches of Water:
  h_m = last manifold pressure (entrance to impact nozzles)
  h_b = line pressure, first manifold
  h_d = pitot-tube kinetic pressure
  h_n = orifice differential
  h_o = impact-tube differential
  h_a = pitot-tube differential
  h_s = static pressure, downstream orifice tap
Temperature in Degrees Fahrenheit:
  t_o = impact-jet temperature
  t_r = room temperature
  t_m = last manifold temperature
  t_b = line temperature, first manifold

Density of Fluid, Pounds per Cubic Foot:

γ_o = density of air at outlet of impact nozzle

γ_n = density of air at downstream side of orifice plate

γ_b = density of air at location of pitot tube

Diameter in Inches:

d_o = impact-tube diameter

d_n = orifice diameter

D = pipe diameter

TABLE 5 ORIFICE TEST

Log Sheet No. 574. Pipe diam. = 12.08 in.; D^2 = 145.926; ratio 50.21 per cent; Barometer, 29.28 in.; inches of water (p_o), 398; humidity per cent, 45; speed, 1800 r.p.m.; Tube No. 5: d_o = 4.004 in.; d_o^2 = 16.032; K_o = 93.60; K_n = 43.89; K_b = 874.099. Tube No. 4: d_o^2 = 3.998 in., d_o^2 = 15.984; K_o = 92.40. Date, 4–12–22.

Conn. B_5	Sta. h_s	Dif. h_n	K_a per h_n	$\sqrt{y_n}$, h_s & t_m	$\sqrt{h_n}$	G_n	$C_n = G/G_n$
A1	4.08	1.56	0.998	2716	1.249	148.6	0.682
2	4.08	1.55	0.998	2716	1.245	148.2	0.684
3	4.08	1.53	0.998	2716	1.237	147.3	0.688
4	4.08	1.51	0.998	2716	1.229	146.3	0.693
5	4.08	1.49	0.999	2716	1.221	145.4	0.698
6	4.08	1.48	0.999	2716	1.217	144.8	0.702
7	4.08	1.48	0.999	2716	1.217	144.8	0.702
8	4.08	1.48	0.999	2716	1.217	144.8	0.702
9	4.08	1.48	0.999	2716	1.217	144.8	0.702
10	4.08	1.48	0.999	2716	1.217	144.8	0.702
11	4.08	1.48	0.999	2716	1.217	144.8	0.702
12	4.08	1.49	0.999	2716	1.221	145.4	0.698

IMPACT TUBE

	No. 5	No. 4
1. Impact (h_o)	4.00	4.00
2. K_a (per h_o)	0.998	0.998
3. $\sqrt{y_o}$ (p_o & t_o)	0.2705	0.2705
4. $\sqrt{h_o}$	2.000	2.049
5. $G_o = K_o\,K_a\,\sqrt{y_o}\,\sqrt{h_o}$	50.44	
6. $G_o = K_o\,K_a\,\sqrt{y_o}\,\sqrt{h_o}$	51.04	
7. G	101.48	

PITOT TUBE

1. Line Pressure (h_b) 5.55
2. Dynamic (h_d) 5.82
3. Tube Diff. (h_a) 0.34 $\sqrt{h_a}$ 0.583
4. K_a (per $h_d - h_b$) 1.000
5. $\sqrt{.b}$ ($p_o - h_b$ & t_b) 0.2718
6. $G_b = K_b\,K_a\,\sqrt{y_b}\,\sqrt{h_a}$ ... 138.5
7. $C_b = G/G_b$ 732

$Q = G/0.0764 = 1328$; $= t_o = 71$; $t_m = 72$; $t_b = 73$; $h_m = 4.12$.

Factors (constant for a given test):

$K_o = 5.99\ C_o d_o^2$ = impact-tube factor

$K_b = 5.99\ D^2$ = pitot-tube factor

K_a = thermodynamic-expansion factor

$K_n = 5.99\ d_n^2$ = orifice factor

Rate of Flow in Pounds of Air per Minute:

$G_o = K_o K_a \sqrt{h_o \gamma_o}$ for impact tube

$G_b = K_b K_a \sqrt{h_b \gamma_b}$ for pitot tube

$G_n = K_n K_a \sqrt{h_n \gamma_n}$ for orifice plate

Experimental Coefficients:

C_o = impact-tube coefficient

C_n = orifice coefficient $XC' = \dfrac{G_o}{G_n}$

C_b = pitot-tube coefficient = $\dfrac{G_o}{G_b}$

TABLE 6 ORIFICE TEST

Log Sheet No. 575. Pipe diam., 12.08 in.; $D^2 = 145.926$; ratio, 50.21 per cent; Barometer, 29.28 in.; inches of water (p_o), 398; humidity per cent, 45; speed, 1800 r.p.m. Tube No. 5: $d_o = 4.004$ in.; $d_o{}^2 = 16.032$; $K_o = 93.60$; $K_n = 43.891$; $K_b = 874.099$. Tube No. 4: $d_o = 3.998$ in.; $d_o{}^2 = 15.984$; $K_o = 92.40$. Date, 4–12–22.

Conn. A_7	Sta. h_s	Dif. h_n	K_a per h_n	$\sqrt{y_n}$, h_s & t_m	$\sqrt{h_n}$	G_n	$C_n = G/G_n$
B1	4.11	1.45	0.999	0.2713	1.204	143.2	0.708
2	4.10	1.46	0.999	0.2713	1.208	143.6	0.706
3	4.10	1.46	0.999	0.2713	1.208	143.6	0.706
4	4.09	1.47	0.999	0.2713	1.212	144.1	0.703
5	4.08	1.48	0.999	0.2713	1.217	144.6	0.702
6	4.12	1.44	0.999	0.2713	1.200	142.7	0.711
7	4.24	1.32	0.999	0.2713	1.149	136.6	0.741
8	4.48	1.08	0.999	0.2714	1.039	123.5	0.820
9	4.64	0.92	0.999	0.2714	0.959	114.0	0.888
10	4.77	0.79	0.999	0.2715	0.889	105.9	0.961
11	4.81	0.75	0.999	0.2715	0.866	103.0	0.983
12	4.82	0.74	0.999	0.2715	0.860	102.2	0.991

IMPACT TUBE

	No. 5	No. 4
1. Impact (h_o)	4.00	4.20
2. K_a (per h_o)	9.98	9.98
3. $\sqrt{y_o}$ (p_o & t_o)	2.702	2.702
4. $\sqrt{h_o}$	2.000	2.049
5. $G_o = K_o\, K_a\, \sqrt{y_o}\, \sqrt{h_o}$	50.4	
6. $G_o = K_o\, K_a\, \sqrt{y_o}\, \sqrt{h_s}$	51.0	
7. G	101.4	

PITOT TUBE

1. Line Pres. (h_b) 5.55
2. Dynamic (h_d) 587
3. Tube Diff. (h_a) 0.34 [$\sqrt{h_a} = 0.583$]
4. K_a (per h_d–h_b) 1.000
5. $\sqrt{y_b}$ (p_o–h_b & t_b) 0.2781
6. $G_b = K_a\, \sqrt{y_b}\, \sqrt{h_a}$ 138.5
7. $C_b = G/G_b$ 0.732

$Q = G/0.0764 = 132.8$; $t_o = 72$; $t_m = 73$; $t_b = 74$; $h_m = 4.12$.

73 The quantity $K = 5.99d^2$ is arrived at by modifying Equation **[10]** to signify h in inches of water, d in inches, and replacing $Q\gamma$ by G. The quantity K_a is given in Table 7 for the various pressure and orifice ratios. The figures of the table are arrived at by comparing the thermodynamic solution of the flow with the hydraulic solution for the same pressure difference.

74 A large number of additional tables were prepared to facilitate the computations in general. One was prepared for each size of pipe giving the constants d^2, K_n, r, r^2, etc., for the fourteen orifices of the given pipe. Another table was made out

for the values of γ and $\sqrt{\gamma}$ at varying pressures and temperatures to cover the range of the tests. A set of curves was prepared giving the values of K_o for each tube corresponding to the variations of the impact head. With the aid of these tables and curves, the results of the tests were computed immediately at the end of each run and were recorded on the same log sheet.

75 The data of the final tests are recorded on 1625 log sheets filed in chronological order and cross-indexed under the various headings of impact tube, pipe size, and orifice ratio. A log sheet of the impact-tube tests contains a run on a given tube either varying the velocity head at constant setting or the setting at constant

TABLE 7 VALUES OF THE FACTOR K_a CORRESPONDING
TO PRESSURE DIFFERENCE IN INCHES OF WATER

Inches of Water	Orifice Ratios											
	10	20	25	30	35	40	45	50	55	60	65	70
1	1.000	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.998	0.998	0.998
2	0.999	0.999	0.999	0.998	0.998	0.998	0.998	0.998	0.998	0.997	0.997	0.996
3	0.999	0.998	0.998	0.998	0.997	0.997	0.997	0.997	0.996	0.996	0.995	0.993
4	0.998	0.998	0.998	0.997	0.997	0.997	0.996	0.996	0.995	0.994	0.993	0.991
5	0.998	0.997	0.997	0.997	0.996	0.996	0.995	0.995	0.994	0.993	0.991	0.989
6	0.997	0.997	0.997	0.996	0.996	0.995	0.994	0.994	0.993	0.992	0.989	0.987
7	0.997	0.996	0.996	0.995	0.995	0.995	0.994	0.993	0.992	0.990	0.987	0.985
8	0.996	0.996	0.996	0.995	0.995	0.994	0.993	0.992	0.991	0.989	0.986	0.983
9	0.996	0.995	0.995	0.994	0.994	0.993	0.992	0.991	0.989	0.987	0.984	0.981
10	0.995	0.995	0.995	0.994	0.993	0.992	0.991	0.990	0.988	0.986	0.982	0.979
11	0.995	0.994	0.994	0.993	0.992	0.991	0.990	0.989	0.987	0.984	0.980	0.977
12	0.994	0.994	0.993	0.992	0.991	0.990	0.989	0.988	0.985	0.983	0.979	0.974

NOTE: One inch of water corresponds to $(P_2 - P_1)/P_1 = 1/400$.

velocity. A log sheet of the orifice tests contains a run on a given-ratio orifice at constant velocity either varying the upstream A-taps with the downstream constant, or the downstream B-taps with the upstream constant. A complete test for a given-orifice ratio comprises four velocity tests and from five to twelve log sheets for each velocity, part of them with A constant and B varying, and part with B constant and A varying. Each pipe size was tested for fourteen orifice ratios with the exception of the 2-in. pipe, on which the lower-ratio orifices were not completed at the writing of this paper.

76 The log sheets for the higher-ratio tests also included the readings of the pitot-tube differential for the given velocity. From

these readings the theoretical rate of flow was obtained and the coefficient of the pitot tube was computed for the given-pipe size. This coefficient was found to have a fairly constant value, 0.73, for the 6-in., 8-in., 10-in., and 12-in. pipes. In the smaller sizes the coefficient was reduced considerably, showing a value of 0.70 for the 4-in. pipe and 0.66 for the 3-in. pipe. It was also found that the maximum differential was obtained when the beveled opening of the tube was turned at an angle of about 10 deg. from the direction of the flow. This phenomenon could be explained by the increased siphoning action on the complementary opening facing in the opposite direction of the flow.

CHARACTERISTIC CURVES OF ORIFICE PLATES

77   At the completion of a test for a number of orifice plates in a given size of pipe the values of the coefficient XC' were plotted in three sections on large sheets ruled in logarithmic coördinates. The first section represented the so-called A-curves plotted as a function of the upstream distances from the A-runs of the test with the downstream connection at the vena contracta. The second section represented the B-curves plotted as a function of the downstream distances from the B-runs of the test. The third section were A-curves plotted as a function of the upstream distances with the downstream connection at four and one-half diameters of the pipe or the point of complete restoration of pressure.

78   These curves, not given in the paper, represented in substance the form similar to the three main sets of the final curve, shown on Fig. 15 for the 6-in. pipe, except that in the original curves each orifice ratio was represented by a group of lines adjoining the test points of the several velocities for a given ratio. Also in those curves the actual orifice ratios were used, which differed somewhat from the equal divisions of the final curves in Fig. 15. With small exceptions the lines of each group did not deviate much from each other, so that in each case a single line was drawn which represented the average value of the coefficient for the given ratio.

79   From these average lines the points of minimum and maximum were plotted on Fig. 14 as a function of the orifice ratio for the various sizes of pipe, the lower set for the coefficient $(XC')_v$ at the vena contracta, and the upper set for the coefficient $(XC')_p$ at four and one-half diameters from the orifice plate. After the points of the two sets on Fig. 14 were joined by smooth lines for

the given sizes of pipes, the corrected values were obtained for the even ratios in multiples of five and the points transferred to the
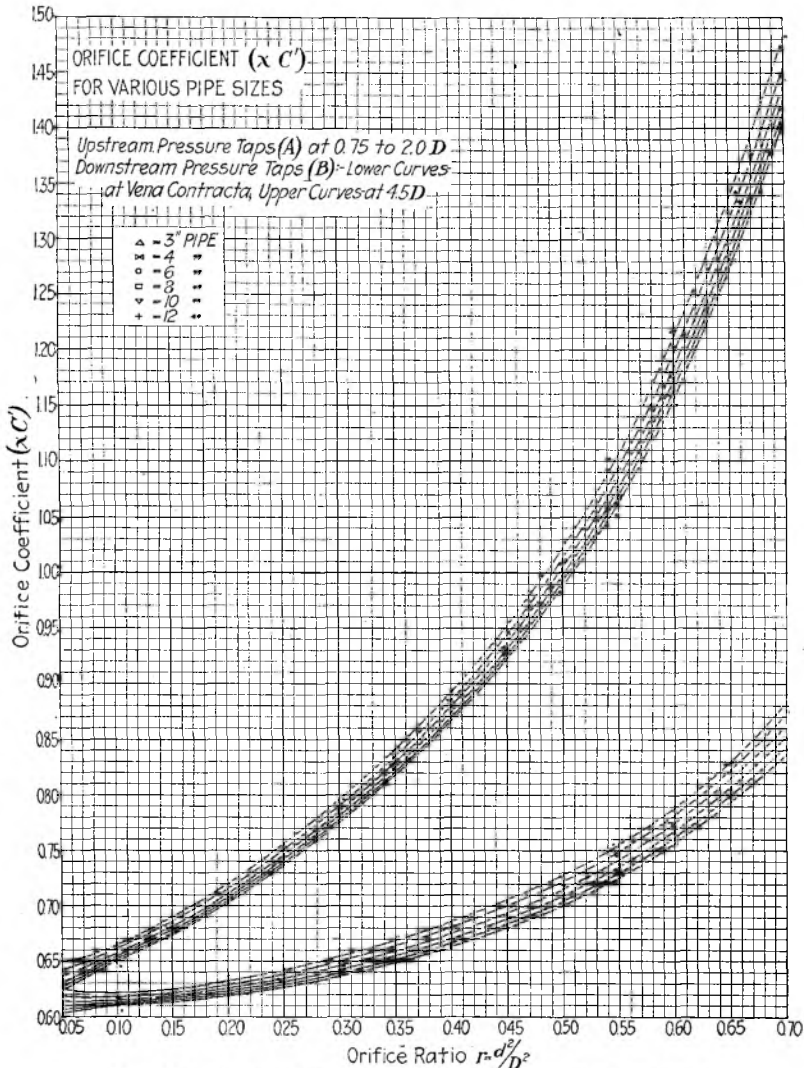

FIG. 14   ORIFICE COEFFICIENTS FOR VARIOUS PIPE SIZES

original curves and compared with the average lines of the nearest ratio. A new line was drawn parallel to the old one to pass through the corrected points for the even ratio. In this manner the effects

of possible errors of observation were reduced, first, by comparison with the similar tests of the same ratio, second, by comparison with the similar tests of various ratios of the same size of pipe, and

(xC') is Defined by $Q = (xC')\frac{\pi d^2}{4}\sqrt{2gh}$. $C' = f(A) \times f(B) \times \sqrt{\frac{1}{1-x^2 r^2}}$; $C_v' = \sqrt{\frac{1}{1-x^2 r^2}}$

$x = \frac{(xC')_v}{\sqrt{1+(xC')_v^2 r^2}}$ C is Defined by $Q = C\frac{\pi}{4}\sqrt{\frac{d^2}{1-r^2}}\sqrt{2gh}$ or $C = (xC')\sqrt{1-r^2}$
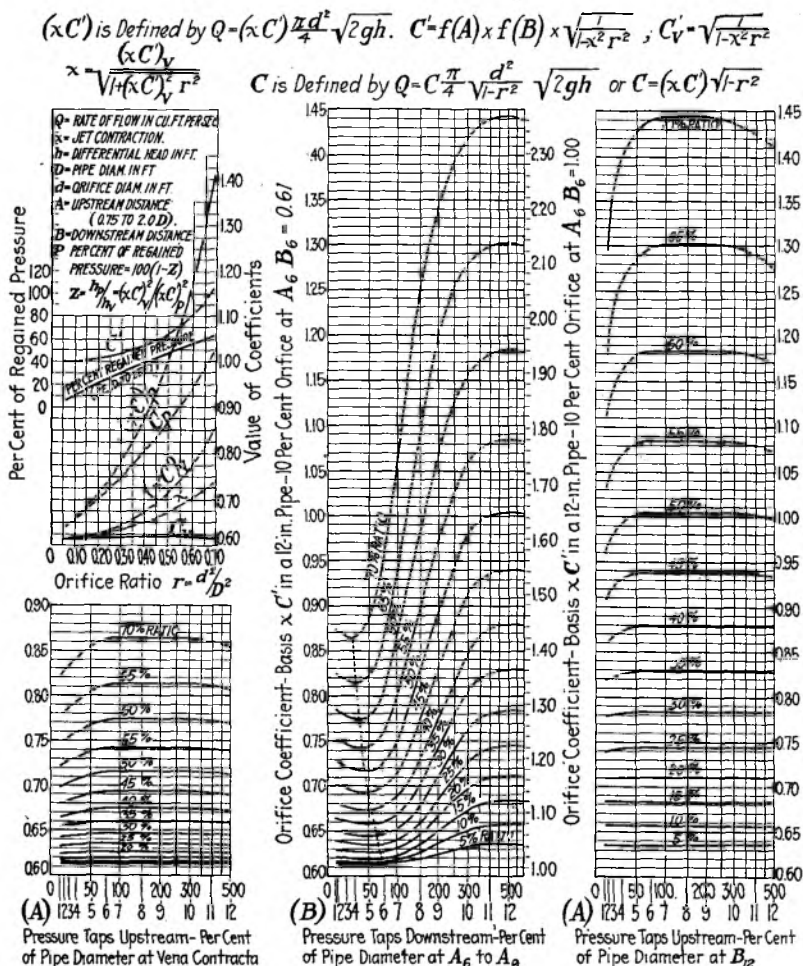
FIG. 15   CHARACTERISTIC CURVES FOR ORIFICE PLATES, 6-IN. PIPE

third, by comparison with the similar tests of the various sizes of pipes.

80   The final curves for the even ratios of the 6-in. pipe are shown in the three main sections of Fig. 15. These three sections give a generalization of the complete work for the given size of

pipe. They point out forcibly the great importance that must be attached to the proper spacing of the orifice connections. In fact,

TABLE 8 ORIFICE COEFFICIENTS FOR 12-IN. PIPE

Ratio $r = \dfrac{d^2}{D^2}$	$(XC')_v$	$(XC')_p$	X	C'	C_v	C_p	$1-Z$
5	0.603	0.624	0.603	1.000	0.603	0.624	0.067
10	0.610	0.650	0.609	1.002	0.607	0.647	0.119
15	0.614	0.676	0.612	1.003	0.607	0.668	0.174
20	0.620	0.703	0.615	1.008	0.608	0.689	0.223
25	0.627	0.736	0.619	1.013	0.608	0.714	0.274
30	0.637	0.774	0.626	1.018	0.608	0.739	0.326
35	0.649	0.818	0.633	1.025	0.608	0.767	0.371
40	0.663	0.867	0.641	1.034	0.608	0.795	0.416
45	0.679	0.923	0.649	1.046	0.606	0.824	0.459
50	0.700	0.987	0.661	1.059	0.606	0.855	04.97
55	0.725	1.063	0.674	1.076	0.605	0.887	0.535
60	0.756	1.157	0.689	1.097	0.605	0.926	0.573
65	0.795	1.273	0.706	1.126	0.605	0.968	0.610
70	0.846	1.413	0.728	1.162	0.604	1.010	0.641

they would seem to indicate that an excessive precision is necessary in determining these points, since a very small change in the tap

TABLE 9 ORIFICE COEFFICIENTS FOR 10-IN. PIPE

Ratio $r = \dfrac{d^2}{D^2}$	$(XC')_v$	$(XC')_p$	X	C'	C_v	C_p	$1-Z$
5	0.606	0.627	0.606	1.000	0.606	0.627	0.066
10	0.611	0.652	0.610	1.002	0.608	0.649	0.122
15	0.615	0.678	0.612	1.005	0.608	0.670	0.177
20	0.621	0.705	0.616	1.008	0.609	0.691	0.224
25	0.630	0.738	0.622	1.013	0.611	0.715	0.271
30	0.640	0.777	0.629	1.018	0.611	0.742	0.321
35	0.651	0.821	0.634	1.026	0.610	0.769	0.371
40	0.665	0.870	0.642	1.035	0.610	0.797	0.416
45	0.683	0.926	0.653	1.046	0.610	0.827	0.456
50	0.704	0.992	0.664	1.060	0.610	0.859	0.496
55	0.730	1.069	0.677	1.074	0.609	0.893	0.534
60	0.761	1.165	0.692	1.099	0.604	0.932	0.573
65	0.800	1.281	0.710	1.127	0.608	0.974	0.610
70	0.851	1.420	0.728	1.163	0.608	1.014	0.641

distance along the steeper parts of the curves might cause a change of several per cent in the value of the coefficient.

81 To eliminate possibility of large errors in the practical

application of the orifice, it is best, therefore, to select only these points for use at which a slight change in the position of the tap

TABLE 10   ORIFICE COEFFICIENTS FOR 8-IN. PIPE

Ratio $r = \dfrac{d^2}{D^2}$	$(XC')_v$	$(XC')_p$	X	C'	C_v	C_p	$1-Z$
5	0.610	0.631	0.610	1.000	0.610	0.631	0.065
10	0.613	0.654	0.611	1.003	0.610	0.651	0.120
15	0.618	0.680	0.615	1.005	0.611	0.672	0.175
20	0.624	0.708	0.619	1.008	0.612	0.694	0.223
25	0.632	0.741	0.624	1.013	0.613	0.718	0.272
30	0.643	0.780	0.631	1.019	0.614	0.744	0.320
35	0.655	0.825	0.638	1.027	0.614	0.773	0.369
40	0.670	0.874	0.646	1.035	0.614	0.801	0.412
45	0.688	0.931	0.657	1.047	0.614	0.831	0.454
50	0.710	0.997	0.669	1.061	0.614	0.863	0.493
55	0.736	1.076	0.682	1.079	0.614	0.898	0.532
60	0.767	1.173	0.697	1.100	0.614	0.939	0.572
65	0.806	1.290	0.714	1.129	0.613	0.982	0.609
70	0.856	1.430	0.734	1.166	0.612	1.021	0.641

would not appreciably affect the coefficient. This condition is obviously fulfilled at the minimum and maximum points, since these

TABLE 11   ORIFICE COEFFICIENTS FOR 6-IN. PIPE

Ratio $r = \dfrac{d^2}{D^2}$	$(XC')_v$	$(XC')_p$	X	C'	C_v	C_p	$1-Z$
5	0.615	0.636	0.615	1.000	0.615	0.636	0.065
10	0.615	0.657	0.614	1.002	0.612	0.654	0.123
15	0.620	0.683	0.618	1.003	0.613	0.675	0.175
20	0.626	0.711	0.621	1.008	0.614	0.698	0.225
25	0.635	0.745	0.627	1.013	0.615	0.722	0.273
30	0.646	0.784	0.634	1.020	0.616	0.748	0.320
35	0.659	0.829	0.642	1.027	0.618	0.777	0.368
40	0.674	0.880	0.650	1.037	0.618	0.807	0.413
45	0.693	0.938	0.662	1.047	0.619	0.838	0.455
50	0.716	1.004	0.674	1.062	0.620	0.870	0.487
55	0.742	1.084	0.687	1.081	0.619	0.905	0.531
60	0.774	1.183	0.702	1.103	0.619	0.947	0.572
65	0.813	1.301	0.719	1.131	0.618	0.990	0.609
70	0.864	1.444	0.739	1.170	0.617	1.031	0.642

points occur at the flat portion of the curve.

82   The A-curves given are restricted to a study of conditions at these two points. These two sets can be used in a similar manner

to select the proper points at which to place the upstream pressure taps. Thus, since the flat parts of the curve occur between points

TABLE 12 ORIFICE COEFFICIENTS FOR 4-IN. PIPE

Ratio $r = \dfrac{d^2}{D^2}$	$(XC')_v$	$(XC')_p$	X	C'	C_v	C_p	$1-Z$
5	0.619	0.642	0.619	1.000	0.619	0.642	0.070
10	0.617	0.661	0.616	1.002	0.614	0.658	0.130
15	0.622	0.686	0.620	1.003	0.615	0.678	0.177
20	0.628	0.716	0.624	1.007	0.616	0.702	0.231
25	0.638	0.750	0.630	1.013	0.618	0.727	0.276
30	0.650	0.790	0.638	1.019	0.620	0.754	0.323
35	0.662	0.835	0.645	1.027	0.621	0.782	0.371
40	0.680	0.886	0.656	1.037	0.623	0.812	0.411
45	0.700	0.946	0.668	1.048	0.625	0.845	0.452
50	0.723	1.014	0.680	1.063	0.626	0.878	0.491
55	0.750	1.096	0.693	1.083	0.626	0.915	0.531
60	0.782	1.197	0.708	1.105	0.626	0.958	0.572
65	0.820	1.318	0.723	1.135	0.624	1.002	0.613
70	0.873	1.464	0.745	1.172	0.624	1.045	0.644

A_6 and A_9, the upstream pressure taps should always be located between these points for the practical application of the orifice.

TABLE 13 ORIFICE COEFFICIENTS FOR 3-IN. PIPE

Ratio $r = \dfrac{d^2}{D^2}$	$(XC')_v$	$(XC')_p$	X	C'	C_v	C_p	$1-Z$
5	0.624	0.649	0.624	1.000	0.624	0.649	0.074
10	0.619	0.663	0.618	1.002	0.616	0.660	0.125
15	0.623	0.688	0.621	1.003	0.616	0.680	0.179
20	0.631	0.718	0.626	1.008	0.619	0.704	0.227
25	0.641	0.754	0.633	1.013	0.621	0.731	0.277
30	0.653	0.795	0.641	1.018	0.623	0.759	0.325
35	0.668	0.841	0.651	1.026	0.626	0.789	0.369
40	0.684	0.893	0.660	1.036	0.627	0.818	0.413
45	0.705	0.953	0.672	1.049	0.629	0.853	0.453
50	0.728	1.022	0.684	1.064	0.630	0.885	0.492
55	0.756	1.106	0.698	1.083	0.631	0.923	0.532
60	0.788	1.210	0.713	1.106	0.630	0.968	0.575
65	0.827	1.331	0.728	1.136	0.629	1.012	0.613
70	0.880	1.480	0.749	1.175	0.629	1.057	0.626

83 The curves in the upper left-hand section of Fig. 15 fulfil both of these conditions selected for good practice, that is, the upstream connections are always between 0.75 D and 2.00 D and the

downstream connections are at the vena contracta or at four and one-half diameters of the pipe. In this section are plotted as a function of the orifice ratio the values of XC', X, C', C and also the percentages of pressure restoration in the pipe. The values of these coefficients are given in Tables 8 to 13 for the various sizes of pipe.

84   The selection of the upstream and downstream distances to be used in general practice must not be taken as a limitation on the use of the orifice to these few points. With the proper care in
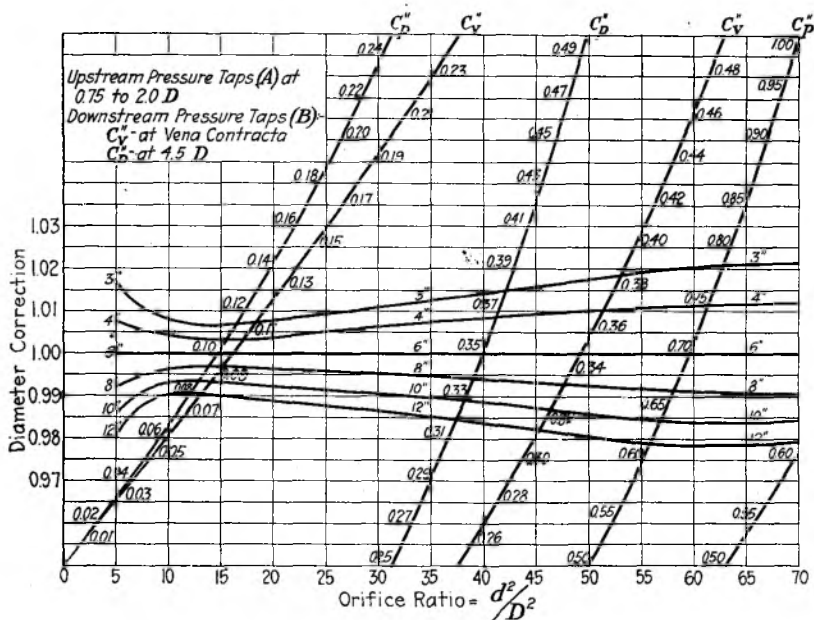
FIG. 16   ORIFICE COEFFICIENT C'' FOR 6-IN. PIPE AND CORRECTION FACTORS FOR OTHER SIZES

spacing the pressure taps, the coefficient corresponding to the exact distance can be easily and precisely obtained from the characteristic curve for the given pipe size.

85   In Par. 68 the orifice coefficient C'' was mentioned as affecting the simplest solution of orifice problems since it relates directly to the known section of the pipe D^2. Accordingly, Fig. 16 was prepared in a convenient form for ordinary use, giving values of C''_v and C''_p as a function of the ratio. To eliminate the necessity of repeating the curves for each size, only those for the 6-in. pipe were

prepared, and additional lines were drawn to scale giving correction factors to be used in obtaining the coefficient for the other pipe sizes.

86   Fig. 17 shows the spacing of pressure taps at the vena contracta in percentage of the diameter length corresponding to the given orifice ratio. The center line is a duplicate of the one passing through the minimum points of the characteristic *B*-curves in Fig. 15. The two outside curves, marked "min." and "max.," show the limits to which the tap may be shifted without varying the coefficients more than 0.25 per cent either way. The actual spacing should be made as nearly as possible to that given by the center
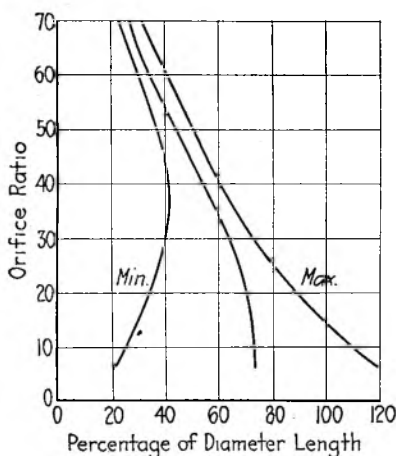
FIG. 17   SPACING OF TAPS AT VENA CONTRACTA

curve, since it is drawn to indicate the exact position of the vena contracta.

CONCLUSION

87   The scope of this paper will not permit of going into the particular details of each individual test. Its main object is to present the results obtained in the Research Laboratory in such a form that they can be applied conveniently.

88   A few remarks may be in order about the most salient points brought out by this investigation.

89   The orifice plate used as a measuring device for the flow of fluids in pipes has a relative accuracy well within the limit of 2 per cent. If reasonable care is applied in the selection of the

location, the proper spacing of the pressure taps, and the proper centering of the orifice between the flanges in the pipe, the possible deviation may be reduced to less than 1 per cent. The maximum variation from the average in any single test seldom exceeded 1 per cent when the differential pressure was above 1 in. of water.

90   The loss of head through the entire region affected by the orifice, which is the differential to the point of complete restoration, is an accurate function of the velocity squared — the same as that of the drop of pressure to the vena contracta. This means that the coefficient C_p is just as reliable as the coefficient C_v. In cases where the pressure difference has an appreciable value, it is even better to use the point of restoration, as the curve is much flatter at that point, in the case of large-ratio orifices, and a deviation from the proper section will not result in any appreciable error.

91   The coefficient of discharge C_v is shown to be very nearly constant for orifices of all ratios. This would mean that the orifice can be treated as a venturi, using the same value of C_v and correcting for initial velocity of approach the same as is done in the venturi tube.

92   The jet issuing from the orifice does not contract to the same extent in the smaller sizes of pipes. This is probably due to the fact that the portion of the flow which is restricted by the orifice has a proportionally lower velocity due to the increased skin friction in smaller sizes of pipes.

93   The variation of velocity pressure from 100 to 300 per cent does not affect the value of the coefficient. This seems to indicate that the name "frictionless orifice" is not misleading. For this reason it is best to use very thin material for the orifice plate to eliminate the friction at the sides of the opening. If the material has to be heavier, it is advisable to bevel the *downstream* side of the opening.

94   The regained head increases very rapidly with the increase of orifice ratio, making the larger-ratio orifice more applicable to cases where the loss of pressure is an important item.

95   Reference is made to the fact that the characteristic curves given in this paper are based upon the assumption that the coefficient of discharge for a 10 per cent orifice in a 12-in. pipe is equal to 0.61. This assumption, however, is borne out by the results of previous experiments by many authorities and can be further substantiated by additional volumetric tests at this point. The experiments, as demonstrated in this work, have shown that the orifice plate is relatively accurate for measuring the flow of fluids for the

varying sizes of pipes and the various ratios of orifices at the proper spacing of the pressure taps. The characteristic curves given in the paper have a complementary scale with the basic value of 0.61 as unity, so that if further experiments should prove that the 10 per cent orifice in a 12-in. pipe has a value somewhat different from the one given, these curves can be applied in the same manner to the new value of the standard.

DISCUSSION

R. J. S. PIGOTT. The paper on Orifice Coefficients is especially interesting in that the values obtained and the characteristics of the stream, when taken in conjunction with the dimensional analysis given in the Fluid Meters Report, afford a means of coördination of practically all of the experimental work on disc orifices. Heretofore these experiments have been thought to show considerable variation from each other, but when allowance is made for the difference of location in up-stream and down-stream taps, the ratio of orifice sizes, pipe sizes and the location of vena contracta, it is found that nearly all the experiments give coefficients substantially in agreement. Allowing for the difference of view of the various experimenters, it is very encouraging that this should be the case, and it is curious that the mathematical analysis of this flow prepared by Dr. Buckingham of the Bureau of Standards for the report should have predicted the characteristics of the orifice as found by Mr. Spitzglass, each working entirely without knowledge of the others' results. It is unfortunate that nearly every experimenter on both venturi tubes and the disc orifices should have used a different system of plotting and comparison; but possibly by trying all the different ways the best method will be adopted by the public who have to use them.

J. W. HOGG. The paper is very complete and covers the measurement of low-pressure air with the concentric straight-edge, thin-plate orifice for all ratios of areas up to 70 per cent in 2-, 3-, 4-, 6-, 8-, 10- and 12-in. pipes. One of its main features is the determination of two coefficients for a given ratio of areas in a given pipe depending upon whether the low-pressure connection is located at the vena contracta or at the point of restoration of pressure. The engineering profession certainly should feel indebted to the author for this extensive work, the results of which are now at its disposal.

The author states in Par. 95 that the 10 per cent concentric orifice in a 12-in. pipe was used as a basis for determining the curves shown on Fig. 15, and that a coefficient for this orifice of 0.61 was assumed as its true value which can be substantiated by actual test. Is the coefficient of this orifice 0.61 for water and steam? No mention is made of these two fluids. Barring the measurement of gas, the real commercial use of a flow meter is for the measurement of steam and water, particularly steam. It would, therefore, be well to know whether the coefficient of the basic orifice, as well as the results derived from its use as a means of calibration are applicable to steam and water, and possibly other fluids heavier or lighter than water, but possessing a different viscosity.

The writer believes that Fig. 17 covering the location of the vena contracta will be very serviceable. It shows the vena contracta to be sharply defined at high ratios of area and to spread out considerably as the orifice becomes smaller. Very often it is desired to measure a flow and an orifice ratio is figured for a given set of conditions, which include a guess at the maximum flow. A corresponding maximum differential is used (usually the range of the differential pressure instrument) to suit this maximum flow. After the orifice is inserted and the pressure connections made at the required distance, it may be found that the maximum flow is either greater or less, in which case it will be desirable to use an orifice with either a larger or smaller ratio. Provided the low-pressure connection was located exactly at the vena contracta, it will not necessarily follow that for the new ratio of areas it will be located at the vena contracta. The location of the low-pressure connection must be changed for this new installation. Fig. 17 shows that a good location for the low-pressure fitting is one-half of a pipe diameter behind the plate for ratios up to 50 per cent, therefore if the flow can be measured between this range without excessive differential head, a distance of one-half pipe diameter behind the orifice may be taken as a fixed location for the low-pressure connection. For the same reason, the fact that the low-pressure connection is at a fixed distance from the plate for the point of restoration of pressure, makes it also a very convenient form of measurement since its location will not have to be changed for varying conditions.

It may be noted on Fig. 14 that the coefficient of discharge for a given ratio of areas decreases as the pipe size increases. The author states in Par. 92 that the jet issuing from the orifice does not contract to the same extent in the smaller size of pipe as it does

in the larger, and he further states this is probably due to the fact that the portion of the flow which is restricted by the orifice has a proportionally lower velocity due to the increased skin friction in the small pipes. It then appears that the ratio of the perimeter of the pipe to the area of the pipe or some other similar function could be incorporated in a equation to be used in figuring the coefficients for sizes of pipe which are entirely too large to be erected in a laboratory for experimental purposes. After this equation is determined, the coefficient of discharge for these large pipes such as 18, 24 and 30 inches could be easily interpolated.

It may be also noted in Fig. 14 that the two sets of coefficients depending upon whether the vena contracta or the point of restoration are used as the location of the low pressure fitting are widely different in value, and the set of coefficients at the vena contracta may be termed as low coefficients, while the set of coefficients at the point of restoration may be termed as high coefficients. It appears from all the data taken in this test that sufficient is on hand to determine a set of coefficients with intermediate values with respect to the other two sets, and this set could be obtained by locating the high-pressure fitting at the point of restoration and the low-pressure fitting at the vena contracta.

Fig. 1, which shows the pressure gradient, is very interesting. The total hydrostatic head in the pipe is shown between the points A_6 and A_7 as $h + \dfrac{v^2}{2g}$ which is equal to the head with no flow, or equal to the head which would be shown by a pitot of unity coefficient. The pressure gradient curve from points A_5 to A_1 shows a decrease in the value of $\dfrac{v^2}{2g}$ and an increase in the value of h which is very peculiar. The writer believes that a possible explanation of this is as follows: Bernoulli's theorem states that the total hydrostatic head of a fluid under flow is equal to the static head at right angles to the flow plus the velocity head plus the friction head; or in symbols,

$$H = h + \frac{v^2}{2g} + h_f$$

Where H represents the total head, h the static head and h_f the friction head. Now at the point A_5 we have,

$$H_{A5} = h_{A5} + \frac{v_{A5}^2}{2g} + h_{A5f}$$

and at the point A_1 we have

$$H_{A1} = h_{A1} + \frac{v_{A1}^2}{2g} + h_{A1f}$$

Since the velocity at A_1 must be greater than the velocity of flow at A_5 from the law of continuity of flow, it follows that

$$\frac{v_{A1}^2}{2g} > \frac{v_{A5}^2}{2g}$$

Now since h_{A1} was found to be larger than h_{A5} by actual test,

$$h_{A1} + \frac{v_{A1}^2}{2g} > h_{A5} + \frac{v_{A5}^2}{2g}$$

If the friction head of flow remains about the same, namely: $h_{A5f} = h_{A1f}$ which might not be the case, it follows that $H_{A6} < H_{A5}$ to a greater extent than it would have been if the static head h_{A1} had decreased from h_{A5} in a ratio depending on the velocity head ratio. Perhaps the author knows the correct explanation.

A. F. SPITZGLASS. The author's evident intention in writing this paper has been to give to the profession a definite and precise knowledge of orifice coefficients and their physical meanings. In addition to its being a report of work done and the theoretical relations involved, the paper can be considered a complete and practical reference for orifice data. For that reason it may be well to elaborate somewhat on the application of this data to practical problems.

Fig. 16 shows a set of curves giving values of coefficients for a 6-in. pipe, and correction factors for pipe sizes varying from 3 to 12-in. This form was originally adopted to obviate the necessity of using a different curve for each pipe size. It was soon found, however, that these curves were unsuitable for determining the proper size of orifice by Equation [11a], Par. 68. The following example brings this out clearly.

Equation [11a] gives us

$$Q = C'' \frac{\pi}{4} D^2 \sqrt{2gh}$$

For a given pipe size, maximum flow and head we obtain the desired coefficient. We then apply this value to the curve to get the proper ratio. In the case of the 6-in. pipe we may read the value of the ratio directly from the main curve since the pipe size correction factor is unity. For the other pipe sizes, however, we must first

find a ratio corresponding to a value somewhat smaller than the actual coefficient. After several trials, a value may be found such that when multiplied by the pipe-size correction for the same ratio, it will give the desired coefficient, and thus we get the proper orifice ratio.

It seems best, therefore, for practical work in calculating orifices, that separate curves be used for each size of pipe. The values for determining these curves could be obtained from Tables 8 to 13 by multiplying the values given in the first column for (XC') by the orifice ratio (r).

Par. 91 mentions the similarity between the coefficients of discharge C_v as given in the equation

$$Q = C_v \frac{\pi}{4} \frac{d^2}{\sqrt{1 - r^2}} \sqrt{2gh}$$

with the coefficient of discharge C for the venturi tube. In Fig. 15 the value of C_v is shown to vary from about 0.61 to 0.62, or approximately 2 per cent. For smaller sizes the value of C_v shows much more variation.

It has been mentioned in this paragraph that since this coefficient remains nearly constant we can use some average value and find our constant for any ratio merely by correcting for velocity of approach as is done in the venturi. This statement must be qualified then as referring only to such cases in which a high degree of accuracy is not necessary. To obtain the true value of the coefficient from the value of C_v we must get this value exactly from a curve and then divide by $\sqrt{1 - r^2}$. Since this involves an extra step in the calculations, the coefficient C'' was adopted as the standard, and may be obtained directly from the curve for any ratio.

Since the completion of the tests the objection has been raised that the Ellison gages cannot be relied on to give results within the limits of accuracy necessary for laboratory work, unless calibrated individually against some absolute standard. Lest this cause reflection to be cast upon the value of the data given, it seems necessary to explain the methods adopted to overcome this difficulty.

From the description given previously it is evident that each test was essentially a comparison of two similar functions of the pressure head at two different points in the stream. Neglecting the corrections applied for change in area, specific gravity, etc., the coefficient varied as the square root of the ratio of the orifice differ-

ential to the head on the impact nozzle. Thus, only a relative accuracy between the two devices used for determining the pressures was necessary to give the required precision. With this in mind, tests were made on a large number of gages, checking them against each other over the complete range of their scales. Of these, three were finally selected that gave practically identical readings along the entire scale. One of these was used for obtaining the orifice differential and the other two for obtaining the head on the impact nozzle.

To retain this precision it was necessary, therefore, to choose a nozzle of such a cross-section that the two gages would read on the same part of the scale. Furthermore, in averaging the results of any of the tests, most weight was given to those runs in which the two pressures were nearly identical.

GEORGE S. HENDRICKSON. The calibration curves for the impact nozzles show that the coefficient changes when the velocity changes, due to the friction. From my understanding, the coefficient of the venturi tube is given as a constant irrespective of the velocity and the conclusion I draw is that both cannot be correct. Can anyone tell if coefficients of the venturi tube have shown a variation at different velocities?

All the tests were made for a given pipe size in the same pipe by varying the orifice ratio. In commercial pipe it is safe to assume that the inside surface of different pipes would not have the same characteristics. One piece might be very smooth and another quite rough. I believe that this might affect the orifice coefficient especially on the larger ratios and higher velocities.

C. A. DAWLEY. Mr. Spitzglass deserves the thanks of the Society and of the engineering profession for undertaking such a formidable series of tests as was required for this paper. The method of relative comparison between two orifices in series insures that the quantities measured are equal, because simultaneous, and this is the only practical method to use for such an extensive series of runs.

The primary reference standard is a 10-per cent (3.825 in. diameter) sharp-edged orifice in a thin plate, installed in a 12-in. pipe and assumed to have a coefficient of 61 per cent. The secondary standards are well rounded flow nozzles as shown in Fig. 6, with an impact tube mounted so as to give the impact head at the center of the flow nozzles. The arrangement of flow nozzles on manifold,

as shown in Fig. 3, is unfortunate from the fact that the air flow has to make three right-angle turns within a short distance, thereby creating violent disturbances or eddies in the flow stream. This piping would naturally produce swirling or helical flow in the vertical pipes leading to the flow nozzles, and would certainly give a higher velocity on one half of the opening of the nozzle than on the other half. The net result of both of these irregularities would be to give a low, and perhaps a variable, coefficient for the nozzles. These conditions of installation probably account for the erratic results shown in Figs. 8 to 13. After reaching a head of 4 to 5 in. of water column the curves are nearly flat and the approximate coefficient read from the curves is as follows:

Nozzle diameter, in.	Coefficient, per cent
1	96.8
2	96.5
3	96.6
4 (No. 4)	96.5
4 (No. 5)	97.5

On the 2-in. nozzle there are apparently two families of points which would give values about 95.8 per cent for the lower and 97 per cent for the higher group. The coefficient of a nozzle of this type has an absolutely definite value and should be higher for the large diameters than for the smaller ones. The writer would expect the 4-in. nozzles to have a coefficient of about 99 per cent at a head of 4-in. water column, if installed under favorable conditions for smooth flow. The fact that the coefficients found do not increase systematically with the diameter and that they are uncertain or variable in some instances, supports the belief that they are influenced by the conditions of installation. It would be of value if Mr. Spitzglass would explore, with a search tube, the whole area of the nozzle outlets as installed, finding the velocity across two diameters at different radii compared with that at the center, and then that the 3- and 4-in. nozzles should be installed in turn directly at the end of the 12-in. pipe in which the disc orifice is located and a further determination made on the relative coefficients.

It difficult is to compare series orifices of widely different size. The head created by flow of the same volume through two similar orifices in series varies inversely as the fourth power (approximately) of the diameter; for example a 1-in. orifice would give about 256 times as much differential as a 4-in. orifice. The writer would

suggest the following method of obtaining coefficients for flow nozzles to be used as primary standards for the disc orifices. Make four 1-in. nozzles numbered 1 *A*, *B*, *C* and *D;* four 2-in. nozzles numbered 2 *A*, *B*, *C* and *D;* two 3-in. nozzles numbered 3 *A* and 3 *B*, and one 4-in. nozzle numbered 4 *A*.

Standardize one of these nozzles, say number 1 *A*, by repeated tests against an absolute volumetric displacement. Then connect numbers 1 *A* and 1 *B* in series and take comparative readings which will show the difference, if any, between these two and by comparison with the absolute tests on number 1 *A*, will give an exact coefficient for number 1 *B*. Similarly with the other 1-in. nozzles. Then put all four 1-in. nozzles in parallel and connect in series with them nozzle number 2 *A*. The drop across the four 1-in. nozzles will be about the same as across one 2-in. nozzle. This will enable finding the coefficient of number 2 *A* and in the same way the other 2-in. nozzles. Then try two of the 2-in. in parallel against each of the 3-in. nozzles and finally four of the 2-in. against the 4-in. nozzle. This permits building up by relative methods, the exact coefficients of nozzles of widely different capacity, at heads all of the same order, with a minimum number of absolute tests on one size.

The most important point settled by Mr. Spitzglass's paper is the location of the vena contracta and the point of maximum restoration of pressure beyond the disc orifice. For the range of heads covered by his tests, these results should stand regardless of any minor inaccuracy in the coefficients of the impact flow nozzles as found.

E. G. BAILEY. The work represented by the data given in this paper is very extensive and should form a valuable contribution to the important subject of metering the flow of fluids. It is unfortunate, however, that the author has deemed it best to present the data in such form that it cannot well be correlated or compared with other data previously presented to the Society on a similar subject. I refer particularly to the paper by Horace Judd[1] submitted at the Spring Meeting, 1916, on Experiments on Water Flow through Pipe Orifices.

In Professor Judd's paper as well as in other works published on this subject the orifice ratio, which is a very important factor in comparing results, has been used as $\dfrac{d}{D}$ while Mr. Spitzglass

[1] See *Trans.* vol. 38, p. 331.

prefers to use $\dfrac{d^2}{D^2}$. This makes it necessary for anyone desiring to compare results to recalculate and replot all curves.

It is also very unfortunate that Mr. Spitzglass did not have a standard or basic measurement upon which to start the comparison. The flow nozzles were calibrated on an assumed coefficient of one orifice, then the orifices were recalibrated on the basis of the flow nozzles. The same flow nozzle could not be used for all the different sizes of pipe so that the final results are rather far from a definite absolute basis. I believe the results as a whole give coefficients too high. I also believe the paper shows more difference between the coefficients of different sizes of pipe than actually exists. While most of the data may be within 2 or 3 per cent of correct absolute value, I think in the present state of the art greater accuracy is expected of the meter manufacturer. It is hoped that some subsequent tests can be made to substantiate or modify these absolute values as mentioned by Mr. Spitzglass in the last sentence of his paper.

Referring to Fig. 1, the right-hand view does not show the true stream lines on the inlet side of the orifice. The particles next to the wall of the pipe continue until they strike the orifice plate and then come in at right angles. The slight building up of pressure near the inlet side of the orifice is due to the reaction as the flowing fluid is diverted towards the center of the pipe. This right angle motion is also responsible for the vena contracta, the path of the stream on the outlet side of the orifice following the resultant of the two substantially right angled forces. At a distance in from the outer circumference of the pipe on the inlet side of the orifice the stream curves somewhat as shown. This, I think, explains the phenomenon of the pressure increase better than is given in Mr. Spitzglass's paper.

It would be interesting to know why Mr. Spitzglass has limited his test to a 70 per cent ratio orifice which is equivalent to 83.70 diameter ratio.

The means for measuring the differential pressure has evidently been confined to Ellison gages. No mention is made of calibrating them. I think it is necessary to do so as slight variations in the diameter and straightness of the glass tube introduce very appreciable errors in this class of work. Such calibration should go to some basic standard as merely checking for zero reading and leveling is not sufficient. Perhaps errors due to this

cause have been eliminated by smoothing out the curves when plotted.

The per cent "regained pressure" on the outlet side of the orifice as plotted in the upper left hand part of Fig. 15 and the location of connections at vena contracta as shown in Fig. 17 agree very closely with data submitted by the writer to members of the Research Committee on Fluid Meters some two years ago.

The use of circular concentric orifices gives no latitude as to the location of the vena contracta. This is rather annoying when high hub flanges are encountered; also when a pipe is tapped for an orifice of one capacity and later an orifice of a different capacity is to be installed. This may require retapping the connections at a comparatively short distance away so that it cannot be accomplished without going to another position on the circumference of the pipe. I have found it very advantageous in such conditions to use eccentric and segmental orifices as shown in Fig. 18.

It is interesting to see the attention being focused upon the thin plate orifice in pipe lines for the measurement of fluid. There is no question but what it has advantages over all other forms of primary devices as to accuracy and reliability as it is not so likely to become fouled up with scale, dirt and sediment as in the case of pitot tubes, venturi tubes and flow nozzles.

JOHN L. HODGSON. The writer has read with interest Mr. Spitzglass's paper on Orifice Coefficients which repeats work which he briefly summarized in Fig. 18 of his paper on the Commercial Metering of Air, Gas and Steam which was read before the Institute of Civil Engineers in April, 1917.

He would like to offer the following comments and criticisms:

1   The contour of the impact nozzles shown in Fig. 6 is unsuitable for low-pressure work, as the effect of viscosity, which is most marked at low flows, alters the shape of the stream lines, and hence the distribution of velocity across the section. The variation of the coefficient of discharge with p_2/p_1 for such a nozzle is shown at I, Fig. 17 of the paper above referred to. It will be seen by comparing curves I and II of that figure that for values of p_2/p_1 which are above the critical value (i.e. when p_2/p_1 is less than about 0.527), the coefficient of discharge changes very little with p_2/p_1 (i.e. with velocity) even though there are great differences in the contours of nozzles I and II. This, however, is not the case for pressure ratios (and velocities) below the critical; hence a nozzle contour

which was suitable for Mr. De Baufre's purpose was entirely un-
suitable for that of Mr. Spitzglass, where it was essential to work
at values of p_2/p_1 which were very nearly unity.

2 It is stated in Mr. Spitzglass's paper that the point of
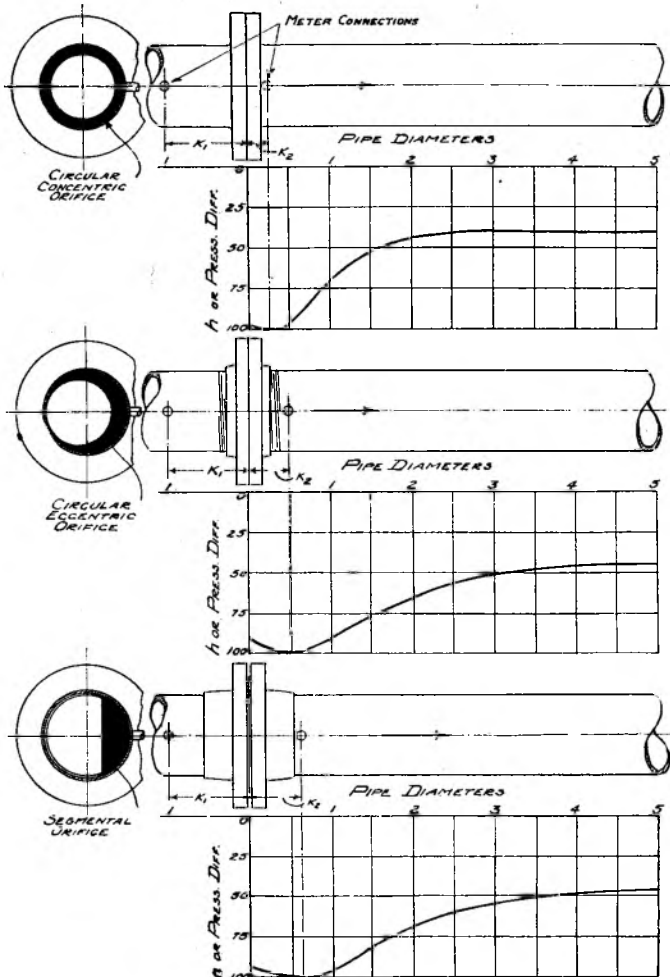

FIG. 18. ECCENTRIC AND SEGMENTAL ORIFICES

maximum recovery is 4.5 diameters on the downstream side of the
orifice, and that this position is independent of the velocity and of
the orifice area ratio. More extended tests covering a greater

range of velocities and pressure hole positions would have shown that the point of maximum recovery varies

    a With the velocity of the air,

    b With the roughness of the pipe, and

    c With the orifice area ratio.

The proposal to use pressure holes further downstream rather than the vena contracta for flow measurement purposes is, according to the writer's tests suitable only for the most approximate measurements (unless the orifice has been calibrated in its own pipe line) as variations in the roughness, and — in the case of large orifice ratios — the diameter of the pipe, cause very considerable variations in the flow coefficient.

    3   It is unsatisfactory to use circular orifices for area ratios greater than 50 per cent, as small errors in centering, or in the diameter of the pipe upstream or downstream of the orifice cause considerable errors in the measurement. Assuming then that it is only necessary to choose suitable positions for the pressure holes for orifice area ratio of less than 50 per cent, it will be seen on reference to Mr. Spitzglass's Fig. 17 that if the downstream pressure hole is drilled half a diameter on the downstream side of the orifice instead of in the best position shown in that curve, no appreciable error is made in the discharge coefficients of the orifices. The writer has used this simple rule to enable his clients to fix the best position of the downstream pressure hole for some eight years past.

    4   For many reasons the most reliable position for the pressure holes is in the plane of the orifice as shown at III, and IV, in Fig. 17 of the writer's paper above referred to. It is a matter for regret that Mr. Spitzglass determined no pressures at these particular points.

    5   The writer thinks it may be of interest to point out that all the tests could have been carried out on one diameter of pipe had the VDW/μ relation been used, where

    V is the velocity of the air,

    D is a linear dimension, say the diameter of the orifice,

    W is the density of the air, and

    μ is the absolute viscosity of the air.

Had the orifices been similar, or had the edges been bevelled off on the downstream sides so that the ratio thickness of edge to diameter of pipe was kept constant, only one set of tests would

have been necessary to determine the coefficients of discharge for orifices of any area ratio for any diameter of pipe.

The VWD/μ relation does not, of course, apply when p_2/p_1 differs appreciably from unity, nor could it be applied to a range of pipes where the relative roughness varied considerably. No appreciable error would, however, have been made in using it for the sizes of pipes and values of p_2/p_1 with which Mr. Spitzglass worked.

THE AUTHOR. It is very gratifying indeed to note that the paper has aroused so much interest and discussion. I will endeavor to cover the various opinions as they were brought up by the members.

Mr. Pigott stated, with reference to the Fluid Meter Report, that nearly all the experiments on record gave substantially the same coefficients for the disc orifice, but he regrets that every experimenter should have used a different system of plotting and comparison. Mr. Pigott, being the chairman of the Fluid Meter Committee, is well familiar with the details of this work and he understands that the process of correlating and comparing the various experiments naturally belongs to the Fluid Meter Committee, or to the public who use the experiments, and not to the individual experimenters.

Mr. Hogg raised the question whether the coefficient 0.61 for the 10-per cent orifice in a 12-in. pipe is applicable for water and steam, as' well as for air. The dimensional analysis given in the Fluid Meter Report shows that the values of the coefficient depend on the kinematic viscosity of the fluid, but from all experimental data available water, steam and the common gases show no difference in the coefficient of the orifice.

Mr. Hogg also suggested that a distance of one-half diameter should be adopted as the low-pressure connection of the orifice. This method has been used by many experimenters, but there is no advantage in adopting it for general practice. In a high-ratio orifice it is very important to place the connection at the proper point and it is best to adhere to this practice. If at any time the orifice is to be changed, it is not necessary to change the connection, as the difference in the factor can be easily obtained from the curves in the paper.

Mr. Hogg asked whether an equation could be derived to determine the effect of pipe size upon the coefficient of the orifice from the relation of the mean hydraulic radius as pertaining to

the friction drop of pressure. The dimensional equation referred to is supposed to correlate the results of tests so that the data of one size of pipe will apply to other sizes by following the law of dynamical similarity in the construction of the orifices.

Mr. Hogg suggested that an intermediate coefficient be determined by locating the high-pressure tap at the point of restoration and the low-pressure tap at the vena contracta. This is a very
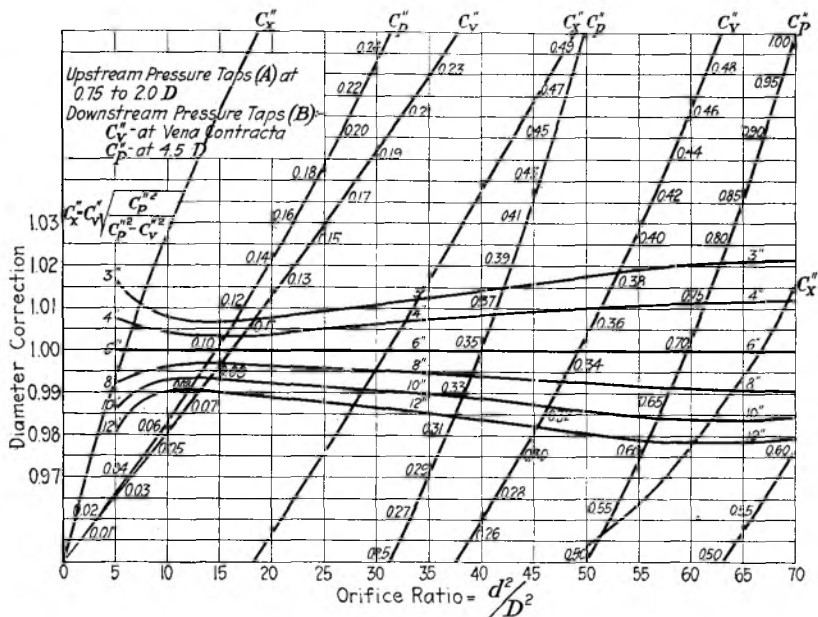

FIG. 19   ORIFICE COEFFICIENT C_x'' FOR 6-IN PIPE AND CORRECTION
FACTOR FOR OTHER SIZES

good suggestion and to take care of it, Fig. 19 is added, which is a modification of Fig. 16, showing in addition the values of

$$C''_x = C''_v \sqrt{\frac{C^2_p}{C^2_p - C^2_v}}$$

It will be noted, however, that the coefficient C''_x is intermediate only at high ratios, crossing the value of C''_p at 51 per cent, while at low ratios it is much higher than any of the other coefficients, so that the main advantage of this additional possibility would be increasing the capacity of the meter without the necessity of changing the orifice in the pipe.

Mr. Hogg was wondering how to adapt Bernoulli's theorem to the pressure gradient, shown in Fig. 1. He stated that from the appearance of the figure there is an increase in static pressure between the points A_5 and A_1, while from the nature of the flow there is also an increase in velocity between these two points, which is contrary to the theorem. As the fluid approaches the orifice the outer filaments are obstructed by the wall of the orifice and turned towards the center of the jet where the static pressure is the lowest, due to the increase of velocity pressure. This change of direction is the explanation of the vena contracta, which is the resultant path of the outer filaments of the jet. The static pressure shown at A_1 is slightly increased, due to the change of direction of the outer filaments of the flow.

The suggestions made by A. F. Spitzglass are a slight addition to the work he has done in preparing the results of this paper.

In reply to Mr. Hendrickson's inquiry, I wish to state that the coefficient of venturi tube does vary with the velocity of the flow similar to the variation shown on the impact tube curves. This variation is due to the effect of friction on the approach part of the venturi tube or nozzle. Since the coefficient of friction is generally increased at low velocity, there is a corresponding decrease in the coefficient of discharge, because the additional friction drop increases the relative differential pressure.

Mr. Hendrickson also inquired whether the roughness of the pipe affects the coefficient. From our experience the nature of the surface is not noticeable except at very high-ratio orifices. For that reason we prefer not to use orifices over the 70 per cent ratio of squares in which the effect of the surface becomes noticeable.

I was pleased to note that Mr. Dawley agrees with me on the method of relative comparison of orifices. As he states it was the only practical method to use for such an extensive series of tests.

Mr. Dawley objected to the arrangement of the flow nozzles on the manifold which followed a number of right angle bends. If Fig. 3 is examined carefully it will be noted that the first two turns are really long radius bends and of a size considerably larger than the approach of the flow nozzle. The air flow through any of the pipes loses practically all its velocity when entering the second manifold, which is of 14 in. diameter. The entrance to the third manifold is a long radius bend of the same 14-in. size. On the top of this manifold each riser is over 6 ft. long and the diameter of the riser is about one-half the diameter of the manifold, and is

double the diameter of the flow nozzle. So that, with this construction of approach there should be no disturbance or eddies in the flow stream.

Mr. Dawley's suggestion to explore the whole area of the nozzle was carried out during the test. We found that in case of the 4-in. nozzle, the impact pressure did not vary at all until the impact tube was placed $\frac{1}{4}$ in. from the circumference of the nozzle. At that point it varied about 1 per cent of the total impact and when the impact tube was placed so that the edge of the tube was in line with the edge of the nozzle, the reduction of the impact pressure was only 3 per cent of the total. This variation was the same in either direction of the nozzle, whether in line or across the turn of the flow at the bottom of the riser.

I believe that Mr. Dawley's statement, that the coefficient of a nozzle of this type has an absolutely definite value, is somewhat exaggerated. I am referring to the paper by Wm. L. De Baufre,[1] Calibration of Nozzles for the Measurement of Air Flowing into a Vacuum, presented to the Society in December 1920. In Table 2, page 635, the last column gives what Mr. De Baufre calls the average "weight-flow efficiency" of the various nozzles, which corresponds to our coefficient of discharge. I wish to call special attention to the last three nozzles, Nos. 18, 19 and 20 of the respective diameters, $\frac{3}{4}$, $\frac{7}{8}$ and 1 in. The first has an average coefficient of 0.9361; the second has an average coefficient of 0.9758, while the third has an average coefficient of 0.9598, and since I have used the same design of nozzle we may expect a similar variation in the results.

Mr. Dawley suggests to calibrate a number of nozzles in series to be used as a standard for calibrating disc orifices. I do not understand how the impact nozzle could be used in series and still be open to the atmosphere. If Mr. Dawley infers to calibrate the impact nozzle inside the pipe and correct for the static pressure, it would involve the old troubles of the regular pitot tube and the calibration inside of the pipe could not be compared to the one open to the atmosphere.

Mr. Bailey objected to the method I used in the paper to plot the results of the test on the basis of diameter square instead of diameter ratio, which he says was the basis used in Mr. Judd's paper and in other works published on this subject. Referring to Figs. 18 and 20 of Judd's paper, it will be noted that Mr. Judd plotted the coefficient of discharge and the factor of correction for

[1] See *Trans.* vol. 42, p. 621.

velocity of approach on the basis of the ratio of orifice area to pipe area, and not on the ratio of orifice diameter to pipe diameter. If Mr. Judd chooses to call a $2\frac{1}{2}$-in. orifice in a 5-in. pipe a 50 per cent orifice, while the results obtained with this orifice are plotted on the 25 per cent line in his main curves, it does not entail any difficulty to compare my results with his, when I choose to call it a 25 per cent orifice when it really amounts to that figure in the actual comparison of results.

There is another very elaborate paper on this subject by Holbrook Gaskell, Jr., published in the *Proceedings* of Civil Engineers, London, Vol. 197, on The Diaphragm Method of Measuring the Velocity of Fluid Flow in Pipes, and throughout this paper all the results are based on the ratio of areas or diameters squared, and not on the ratio of diameters. It is rather unfortunate that this method is not adhered to by all the manufacturers of fluid meters, as it deprives the user of the advantage of visualizing the flow through the orifice as compared with the flow through the pipe. When I think of a 5-in. orifice in a 10-in. pipe, I see before me a jet of 25 circular inches, as compared with an extension of 100 circular inches, which is 25 per cent of the total area. I cannot imagine a jet as a diameter but as a diameter square.

Mr. Bailey further objected to the standard or basic measurement upon which the comparison is based. I believe he will agree with me that the coefficient of a 10-per cent orifice in a 12-in. pipe is very close to 0.61, no matter what standard will be used for all the different sizes of pipes. In some cases two and three nozzles were used for calibrating one orifice, but each nozzle was calibrated separately, and therefore, the results are based on the same adopted standard. It is a common error to confuse the absolute accuracy of a device with the probable accuracy of each individual test performed for the purpose of calibrating the given device.

This point of difference was brought out very forcibly by Mr. Alfred Cotton in his paper The Accuracy of Boiler Tests,[1] presented to the Society in May 1922. Any individual test may effect the variation in the results for many particulars not at all adherent to the device, and the reason we are justified in drawing conclusions from the average results of a large number of individual tests is because the probabilities are that the errors will vary in both directions. Additional tests are being carried on now with a large holder to substantiate the standard adopted in

[1] See Paper No. 1841, this volume.

the paper, and these will be reported as soon as they are completed.

When I wrote the paper, I was familiar with Mr. Bailey's explanation of the vena contracta, but I never agreed with him that the particles of the fluid close to the walls of the pipe are actually turning on the square when they reach the orifice plate. If a particle has any momentum at all when it strikes a plane in the direction of the flow, it will rebound 180 and not 90 deg. as Mr. Bailey would have it in his analysis. The pressure gradient, shown in Fig. 1, was drawn from the actual tests recorded on log sheets 574–575. The jet outlined in the profile of the pipe was meant to show the boundary of the so-called region of disturbance, caused by the orifice plate. Inside that region there are numerous eddy-currents flowing in every direction, forwards, sideways and even backwards, and this is true on both the inlet and outlet sides of the orifice plate. The pressure gradient, as shown on Fig. 1, clearly indicates the extent of that disturbance and the fact that the pressure increases gradually from A_5 to A_1 is a further proof that the direction of the flow is beginning to change at A_5 and not at the very plane of the orifice.

With reference to higher ratio orifices, the tests were not limited to 70 per cent, but the results obtained for higher ratios indicated that extreme accuracy is required in centering the orifice plate and in measuring the pipe diameter. Higher ratios are being investigated at present and the results will be reported later.

The calibration of gages used for measuring the differential pressure is explained in the discussion by A. F. Spitzglass.

Mr. Hodgson's objection to the contour of the impact nozzle shown in Fig. 6 does not apply to this case, because in my tests the nozzle was only a means of conveying a stream of fluid and measuring the velocity pressure with an impact tube faced against the stream. This case is entirely different from the coefficient of discharge referred to in Fig. 17 of his paper where the velocity pressure was represented by the difference between the inlet and the outlet of the given nozzle. In my case the nozzle was used similar to the method employed by Mr. Sanford A. Moss [1] in his paper, The Impact Tube, presented to the Society in December 1916. In fact the preliminary tests referred to in my paper were made with a nozzle tube, similar to the one shown in Fig. 1 of Mr. Moss' paper. In the final tests the design adopted by Mr. De Baufre was used to see whether the change in design made any difference.

[1] See *Trans.* vol. 38, p. 761.

In both cases the same velocity pressure was obtained throughout the full area of the nozzle, as I explained in my reply to Mr. Dawley. There was only a change of 3 per cent in the velocity head, which would mean approximately 1.5 per cent velocity at the very circumference of the jet. This proved conclusively that the form of rounding the nozzle is immaterial when used in connection with an impact tube for obtaining the velocity pressure.

Mr. Hodgson states that the point of restoration or maximum recovery of pressure should vary

    a With the velocity of the air,
    b With the roughness of the pipe, and
    c With the orifice area ratio.

In our tests the point of restoration did not vary when the velocity pressure was changed from 1 to 6 in. of water. Neither did the final point vary with the orifice ratio but the approach to the maximum recovery shows a different shape in the larger ratio orifice. The roughness of the pipe should have no effect on this point because the stream does not touch the walls of the pipes until it comes to this point. From this point farther on, the pressure drops, due to the effect of friction in the pipe. A 4.5-diameter ordinate on Fig. 18 in Mr. Hodgson's paper would cross the maximum with a slight exception of the two upper curves. The use of pressure taps at the point of restoration is recommended because the curve of the coefficient is much flatter at that point in the case of the high ratio orifices.

Mr. Hodgson does not recommend the use of orifices over 50-per cent ratio, for the reason that small errors in centering, or in the diameter of the pipe will cause considerable error in the measurement. It is a very good suggestion to emphasize the necessity of centering the orifice and of measuring the exact diameter of the pipe when larger ratio orifices are used. With the method of centering, shown in Fig. 6, and the correct measurement of the diameter of the pipe, the results appeared to be equally reliable up to an orifice ratio of 70 per cent. As stated in the reply to Mr. Bailey, higher ratios are being investigated at present and the results will be reported later.

Mr. Hodgson regrets that we did not take readings of the pressures in the plane of the orifice. This was not necessary, as by extending the numerous points in the first diameter length towards the plane of the orifice, the true pressure could be obtained at any

geometrical point of the given pipe. Similarly by extending the various curves on Fig. 15, you can obtain the coefficient for any geometrical point close or at the plane of the orifice. I can see no reason why the most reliable position for pressure taps is in the plane of the orifice. If the reason is, as Mr. Hodgson explains on page 28 of his paper, because the position of the pressure holes in different sizes of pipes should be geometrically similar, the same reason should apply to the vena contracta which must be geometrically similar for a thin plate orifice and besides the stream of the jet is more defined than at the plane of the orifice. According to our tests both the vena contracta and the point of restoration are geometrically similar on all the sizes of pipes we have tested, from two to twelve inches diameter.

Mr. Hodgson makes reference to the theory of dynamical similarity as applied to orifices in various sizes of pipes. Mr. Pigott referred to the same theory stating that Dr. Buckingham predicted the characteristics of the orifices and the behavior of the jet at the various geometrical distances as found by the test. Obviously many more tests will have to be run on various sizes of pipes before the validity of the geometrical similarity will be established.