ratio orifice plates, namely, for β equals 0.222 and β equals 0.444, remain within the allowable tolerance of ±0.5 per cent with an air-inhalation coefficient as great as 0.25, while the air-inhalation coefficient for the higher diameter-ratio orifice plate, namely, 0.633, must not be greater than 0.08 to maintain the allowable tolerance for the discharge coefficient.

Fig. 8 shows the relationship between the minimum air-inhalation coefficient and cavitation number for various diameter ratio orifice plates to produce optimum noise and vibration suppression. It may be noted that the minimum air-inhalation coefficient required to suppress the vibration and noise increases with a desumcrease in cavitation number.

Conclusion

The results obtained concerning the effects of cavitation on the discharge coefficients of standard sharp-edged orifice plates are summarized as follows:

1 The discharge coefficient K is not influenced beyond the standard allowable tolerances to a minimum cavitation number K_d of 0.2.

2 The incipient cavitation number is approximately 2.5 and is independent of the orifice-diameter ratio in the range of the test orifices, the experimental velocity, and the static pressure.

3 The method of air-inhalation may be employed to suppress the vibration and noise due to cavitation without influencing the orifice-discharge coefficient beyond the allowable tolerance of ±0.5 per cent.

References

1 J. F. Bailey, "Metastable Flow of Saturated Water," Trans. ASME, vol. 73, 1951, p. 1109.

2 G. Ruppel, "Die Durchflusszahlen von Normblenden und ihre Abhängigkeit von der Kantenlänge," *Zeitschrift VDI*, vol. 80, 1936, p. 1381.

3 "Standard on Measurement of Water Quantity With Pipe Orifice," *Journal of the JSME*, vol. 43, 1940, p. 295.

4 "Report of the Joint AGA-ASME Committee on Orifice Coefficients," 1935.

5 DIN 1952, VDI-Durchflussmessregeln, VDI-Verlage, 1948.

6 S. F. Crump, "Determination of Critical Pressures for the Inception of Cavitation in Fresh and Sea Water as Influenced by Air Content of the Water," David W. Taylor Model Basin, Report 575, 1949, p. 4.

DISCUSSION

James W. Ball[3]

The material contained in the paper is very interesting and establishes definitely that the basic laws for orifices are true. Work of this nature signifies progress and increases the confidence of those who use the results. The authors are to be commended for their contribution.

Actually, an examination of basic relationships for orifices confirms the results. The differential head between two pressure taps, one upstream and the other downstream of an orifice in a pipeline, is an indication of the amount of flow through the orifice irrespective of the location of the taps. The change in hydraulic grade between the two taps (differential head) results from three sources: (1) Head to cause the flow through the orifice, (2) head loss due to boundary friction, and (3) head loss due to turbulent eddies. The amount contributed by each of the three sources will vary with the geometry of the jet issuing from the orifice and the distance of the taps from the orifice. For fully developed turbulence and a given orifice, the flow pattern geometry in the pipe does not change noticeably, provided the downstream pipe is kept under back pressures which assures that the jet is surrounded by water. The coefficient of discharge for a given orifice to pipe diameter ratio will be constant for any tap location as long as this condition exists. The location of the upstream tap is not too important. However, this is not true of the downstream tap. A fixed location for the upstream tap will be considered for the following discussion. As the pressure gradient downstream from an orifice is lowered and the cavitation envelope forms and extends sufficiently to alter the flow stream geometry, the coefficient, based on taps affected by this alteration will deviate from the constant value. The smallest deviation will occur for taps least affected by the change in the stream geometry. The stream geometry upstream from the vena contracta remains essentially the same regardless of the downstream pressure; thus the discharge coefficients based on measurements at downstream taps located at or upstream from the vena contracta will not be changed by the presence of cavitation downstream from the orifice. This explains why the coefficient of discharge is essentially constant for the flange taps used in the tests discussed in the paper and why similar results shown in Fig. 9 were obtained in tests at cavitation numbers as low as 0.001 and heads up to 160 feet made in a test facility (Fig. 10) in the Bureau of Reclamation Hydraulic Laboratory. This also explains why the coefficient of discharge decreases abruptly when the downstream tap is located any appreciable distance downstream from the vena contracta as is the case for part of the data shown on Fig. 11. However, the coefficients in these cases remain substantially constant until the hydraulic grade in the "recovery" region moves past the tap location.

As the cavitation envelope below an orifice lengthens due to decreased back pressure and the recovery region moves past the downstream tap, the pressure at this tap is lowered, increasing the apparent differential head between the upstream and downstream taps while neither changing the pressure immediately downstream from the orifice nor the discharge through the orifice. This results in a decrease in coefficient as shown on the curves of Fig. 11. As the cavitation envelope extends and vapor pressure reaches the downstream tap, the coefficient again becomes constant and has a value equal to that for flange taps.

There is a difference in numerical value of the coefficient depending on how far the downstream tap is located from the orifice. This is due mainly to the difference in friction and eddy losses to the various locations. The differences for taps located 0, 2.1, 15, and 36 inches downstream from $2^{3}/_{8}$, $1^{3}/_{4}$, and $1^{1}/_{4}$-in. orifices in a 3-in. standard pipe are shown in the plots on Fig. 11. The differences for the two locations farthest downstream become insignificant for the smallest orifice where the velocities in the pipe are very low and the friction and eddy loss differences become an insignificant part of the total head differential. The shape of the curves, cavitation number K versus coefficient of discharge C, in any case will be essentially the same for both locations in the range where the recovery region moves past the tap. Where the tap is located just downstream from the vena contracta as for the 2.1-in. location, Sta. (3), on the $2^{3}/_{8}$-in. orifice, the coefficient will be slightly larger than for flange taps until vapor pressure reaches the tap (Fig. 11).

A flow nozzle 1.333 inches in diameter (Fig. 12) was tested in the same setting as the three orifices. The data for the nozzle are plotted on both Figs. 9 and 12. The K_d versus C curve on Fig. 9 is quite different from that for orifices, indicating that cavitation does affect the efficiency of this particular shape. Also, for this particular nozzle, there seemed to be a slight change in the value of C with head, the cause of which has not been definitely determined but may be an influence introduced by the shape of the nozzle. The discharge coefficient of this nozzle is affected by cavitation irrespective of the downstream tap location.

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H_1 = Pressure head at upstream flange tap in feet.
H_2 = Pressure head at downstream flange tap in feet.
H_v = Vapor pressure of water in feet.
V_0 = Average velocity through orifice in feet per second.
A_0 = Area of orifice in square feet.
Q = Rate of flow in cubic feet per second.

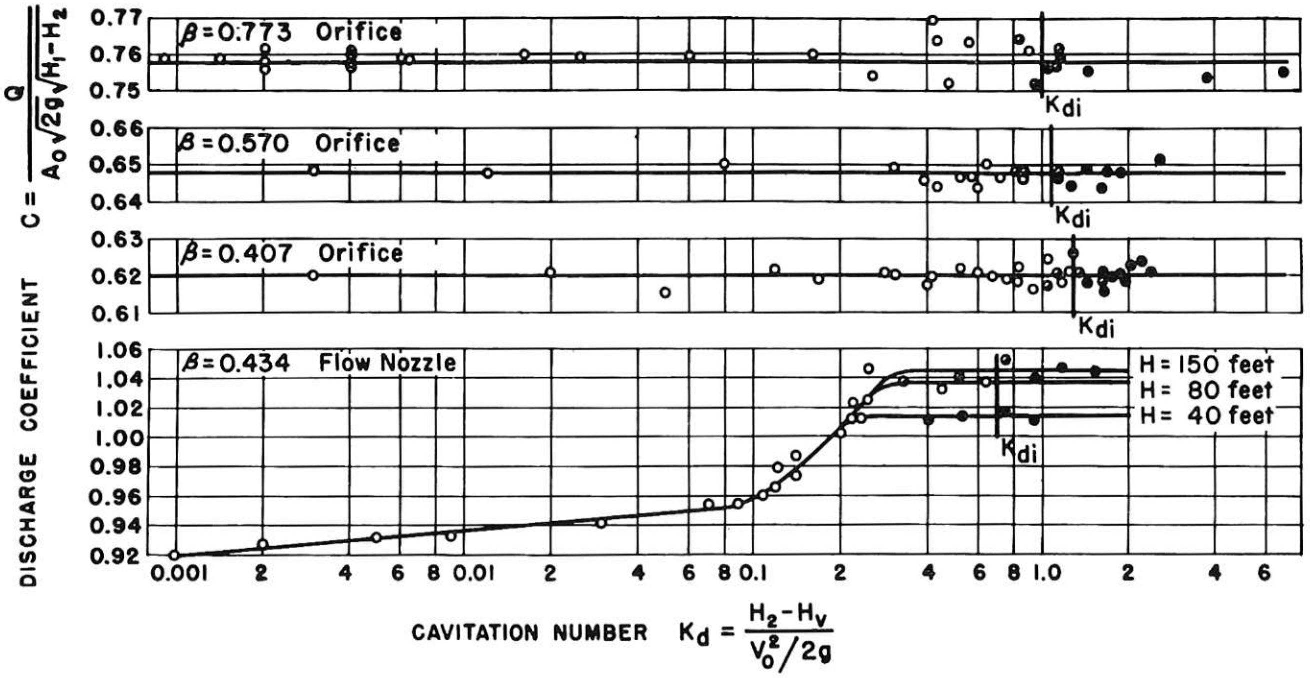

Fig. 9 Variation of discharge coefficient C with cavitation number K_d

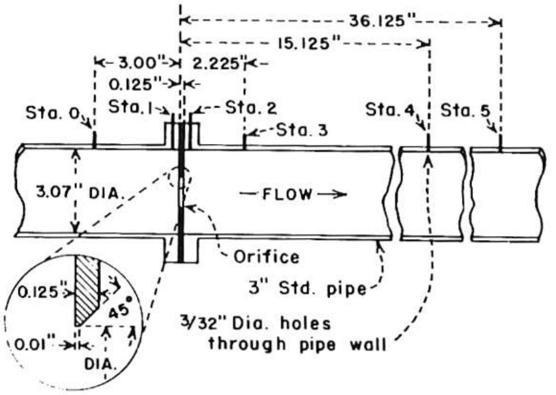

Fig. 10 Test facilities for orifices and flow nozzle

The cavitation data given in the paper are very interesting, and their publication has brought out some interesting facts. The cavitation number for incipient cavitation obtained by ear for the $1^1/_4$, $1^3/_4$, and $2^3/_8$-in. orifices tested in the Bureau of Reclamation Hydraulic Laboratory and based on the relationships given in the paper were 1.3, 1.1, and 1.0, respectively. These values appear to agree reasonably well with the paper; however, the trend is for K_{di} determined by ear to increase with decrease in β rather than increase with β as does line "*L*" which is defined as "where noise and vibration from cavitation became quite apparent." (Fig. 6 of the paper.)

In one series of tests made in the Bureau of Reclamation Hydraulic Laboratory on the $1^3/_4$-in. orifice, the value of K for incipient cavitation, using the relationships given in the paper, did not agree with that given in the paper. Also, an examination of the test results made on two 2.083-in. orifices, placed in tandem in a 3-in. pipeline to serve as a pressure reducing system,[4] indicated poor agreement. In these instances it appeared that cavitation occurred at much smaller values of K than shown in the paper. Check tests on the $1^3/_4$-in. orifice showed the initial tests to be in error. The check tests on this orifice agreed reasonably well with the results given in the paper and it was theorized that a small air leak into the system occurred downstream from the orifice, thus preventing cavitation noise (crepitation) until a lower value of K was reached.

In the tests in which the two 2.083-in. orifices were used in tandem in a 3-in. pipeline (Figure 13), the criterion was that the noise level was acceptable. This point was therefore somewhat above that for incipient cavitation and agreement with the data in the paper could not be expected.

The cavitation number given in the paper is not in a form which could be readily used by designers to determine whether or not there would be objectionable cavitation and vibration in an orifice installation. In studies on valves in the Bureau of Reclamation Hydraulic Laboratory[5] another form of cavitation number was found most useful for this purpose. The same relationship can be applied to orifices in a pipeline. The data for three orifices using this relationship

$$K = \frac{H_x - H_v}{H_T - H_x} \quad \text{and} \quad C = \frac{Q}{A_o\sqrt{2g}\sqrt{H_o - H_x}}$$

are plotted on Fig. 11 where the symbols in both equations are defined.

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[4] L. V. Wilson, "Hydraulic Studies of a Pressure Reducing System for the Transformer Cooling Water—Grand Coulee Power Plant," Bureau of Reclamation Hydraulic Laboratory Report Hyd-308, March, 1951.

[5] James W. Ball, "Cavitation Characteristics of Gate Valves and Globe Valves Used as Flow Regulators Under Heads Up to About 125 Feet," Trans. ASME, vol. 79, 1957, pp. 1275–1283.

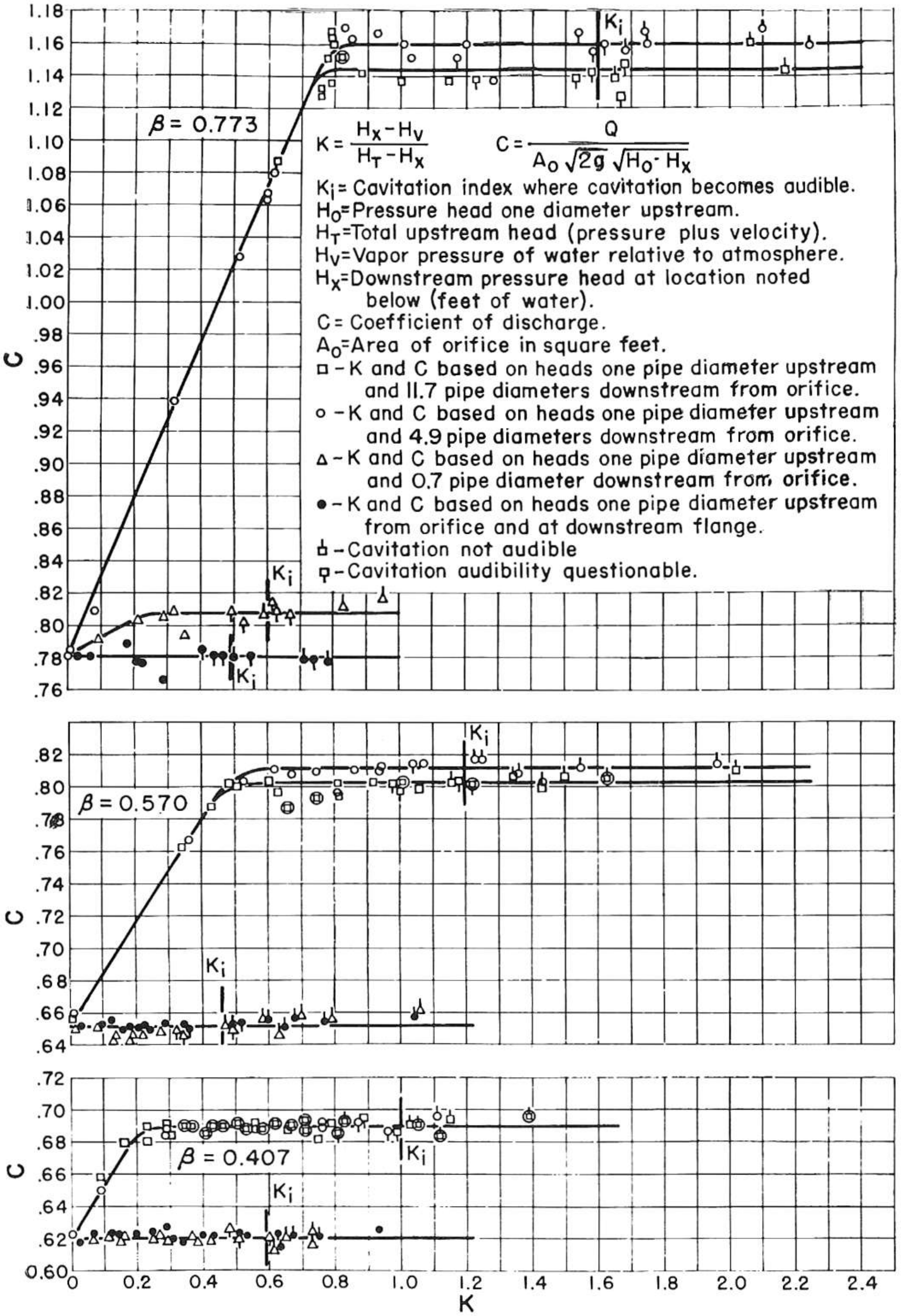

Fig. 11 Variation of discharge coefficient C with cavitation number *K* for orifices $1^1/_4$, $1^3/_4$, and $2^3/_8$-in. diameter

Knowing the critical cavitation number K_i at which cavitation is incipient for an orifice, it is possible to determine the back pressure required to prevent cavitation for a given upstream head, or to compute the allowable upstream head for a given back pressure. It is believed that the variation of K with β', where β' is the ratio of the area of the jet at the vena contracta to that of the pipe, should be somewhat like that shown in Fig. 14. This relationship was obtained by assuming general cavitation just beginning in the pipe immediately downstream and a loss to the recovery pressure downstream equal to the Borda Loss expressed by $H_L = (V_o - V_p)^2/2g$. V_o = velocity of the contracted jet[6] and V_p = velocity in the pipe downstream.

Values of K_i determined by ear for the three orifices and based on the relationship in Fig. 11 for taps located at Sta. 4 and Sta. 5 (4.9 and 11.7 pipe diameters downstream of the orifices) are also plotted in Fig. 14. The curve formed by these values is much

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[6] Contraction coefficient obtained from page 35, "Engineering Hydraulics," by Hunter Rouse.

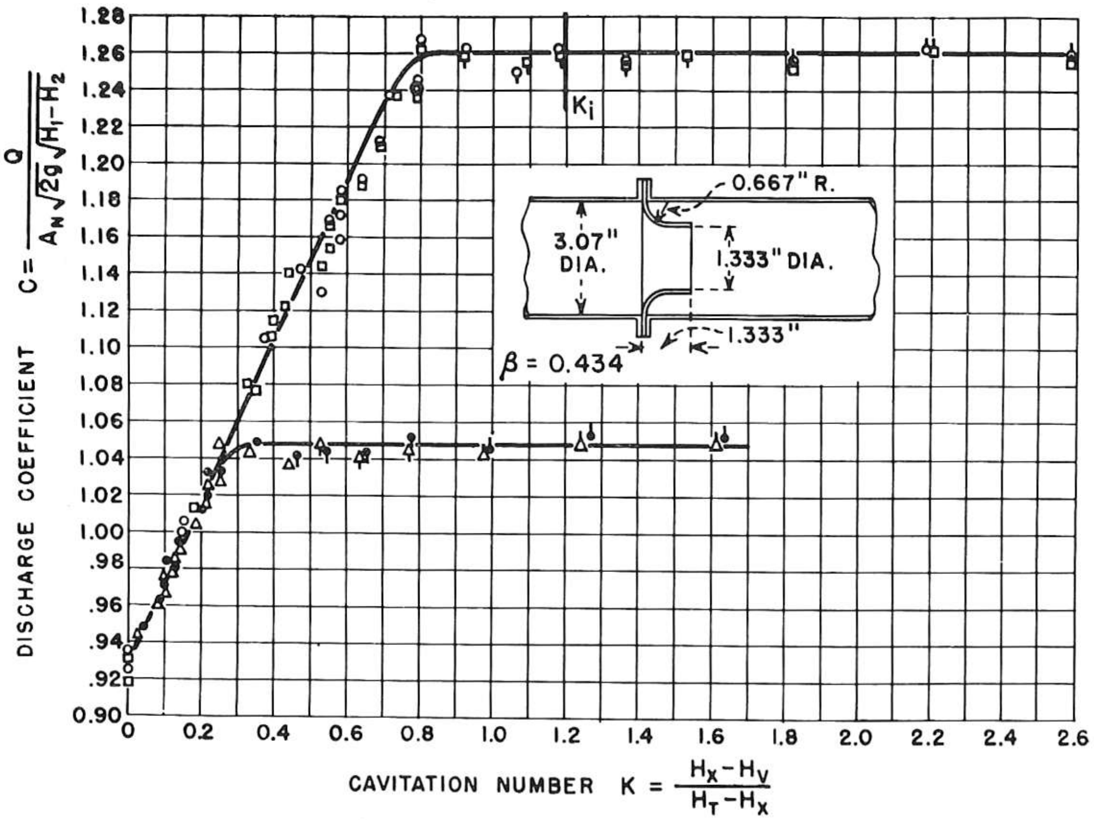

Fig. 12 Variation of discharge coefficient *C* with cavitation number *K* for flow nozzle 1.333 inches in diameter

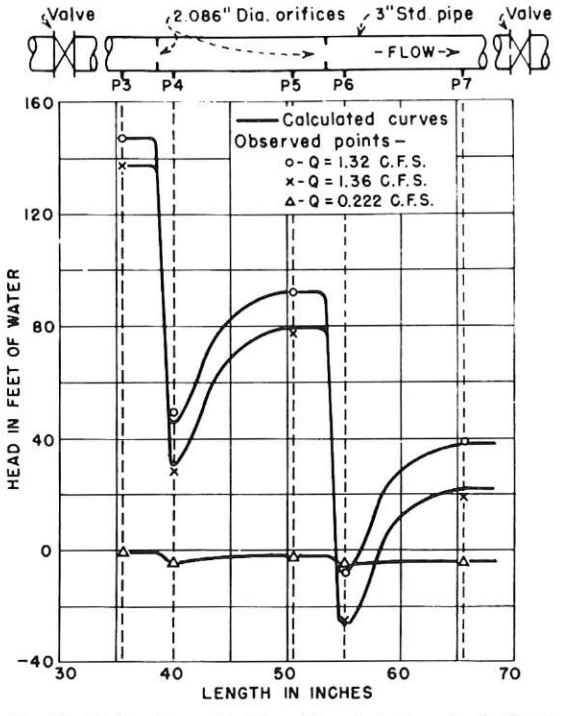

Fig. 13 Hydraulic gradient for orifices in tandem in pipelines

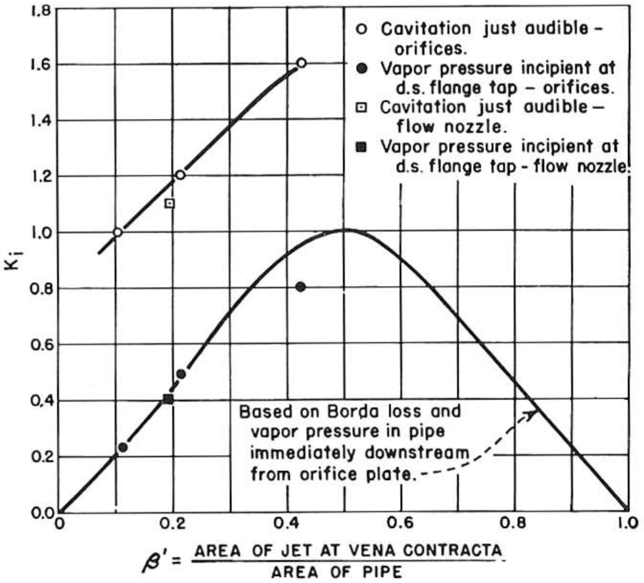

Fig. 14 Critical cavitation number K_i for orifices and flow nozzle

higher than that based on the occurrence of vapor pressure immediately downstream from the orifices and the Borda Loss. This signifies that cavitation occurs before vapor pressure is registered at flange or vena contracta taps.

Several tests on the three orifices were made for conditions where vapor pressure at the downstream flange tap was believed to be incipient. The values of *K* for this condition, based on downstream taps at Stations 4 and 5, were plotted for comparison with the values obtained using the Borda Loss relationship. The *K* values for the orifices, based on heads at Stations 4 and 5 and obtained from plots of the pressure data, were in good agreement, Fig. 14. The agreement is excellent considering that the information was taken from tests not made for that specific purpose, that it was questionable that vapor pressure was incipient at the downstream flange taps, and that it was questionable that the taps were located or could be located to indicate the conditions assumed for the Borda Loss relationship.

The values of K_t for the three different orifices were obtained by ear. The audibility of cavitation was noted for each test run. There were three conditions observed, (1) cavitation definitely audible, (2) cavitation definitely not audible, and (3) cavitation audibility questionable. The third condition gave the most difficulty but was very useful in selecting K_t for each orifice.

It is questionable that cavitation actually exists in all the "manner of cavitation occurrence" definitions given in Table 2 of the paper. It is believed that the bubbles described for a cavitation number of 2.5 are those formed by air being released from solution as the flow passes into the low pressure zone immediately downstream from the orifice rather than vapor cavities. Bubbles formed by air coming out of solution and then moving in the eddy zone downstream, as described in Table 2 for a cavitation number of 1.0, are not necessarily vapor cavities and cannot be considered definite proof that cavitation is present. Air coming out of solution in sufficient quantity may influence the point of incipient cavitation and muffle the crepitation. Similar tests in a water tunnel, using deaerated water, would be of particular interest.

It is of interest at this time to point out that because of relatively high head losses, orifices can be used in tandem for energy dissipation, Fig. 13. However, because of the intense noise and vibration accompanying cavitation, it is important to prevent cavitation by providing sufficient back pressure. Also, it is imperative to consider the fact that wide fluctuations in pressure occur in the eddy zone immediately downstream from the orifice at all times when high-velocity flows are being handled. Because of the critical factors involved it is expedient and wise to make hydraulic investigations before designs employing this principle are used. More interesting facts about orifices will no doubt be forthcoming when studies are made of the transient pressures downstream.

A point of interest concerns measurement of head at pressure taps located downstream from orifices. Wide fluctuations in pressure make it imperative to obtain a sufficient number of readings to obtain average values or use ample damping in the pressure recording units to obtain average values. The consistency of data will depend on the care exercised in recording the head. This factor no doubt is the reason for the variable spread in points on the curves of the paper and this discussion.

The arrangement shown schematically in Fig. 13 has been used to reduce the head from 163 feet to 38 feet for a transformer cooling water system.[4] An installation, using a needle valve for a variable orifice, has been employed successfully in reducing a head of 630 feet to 250 feet to supply and make use of an existing power plant designed for the lower head.[7] In both of these cases it appears that the major portion of the energy in a high-velocity jet discharging into a sudden enlargement is dissipated in the first 5 to 6 diameters length of the enlarged section. This condition of course is not true if a general zone of cavitation is permitted to occur immediately downstream from the point of entry. Extremely high heads may also alter this observed characteristic.

Some work not yet published has been performed by the Bureau of Reclamation Hydraulic Laboratory on the back pressure necessary to prevent destructive cavitation for valves discharging into sudden enlargements of various sizes. Briefly, the tests have shown that cavitation numbers, based on the relationship given in Fig. 11, may be as low as 0.20 without causing pitting of the walls of the sudden enlargement when a diameter ratio, valve to pipe, of 1.75 or more is used. Also, the admission of a very small amount of air near the downstream end of the valve will quiet crepitation immensely.

The standard hydraulic symbols C and K, for discharge coefficient and cavitation number, are used in this discussion. The use of K for both, as in the paper, is somewhat confusing.

Authors' Closure

(Written by F. Numachi)

The authors wish to express their appreciation of the understanding discussion given by Mr. James W. Ball. The data given in his discussion back up the main tenor of their paper. Especially they are grateful for the experimental proof in his discussion that the C-value is not affected by cavitation where the value of cavitation number is not only down to 0.2 but also to 0.001.

He clarified that the K_d versus C-curve of nozzle is affected by cavitation, and the results are obviously useful and interesting.

In the authors' paper, flow measurement by means of standard pipe orifice is the center of their interest, while Mr. Ball gives his opinion on cases where the position of taps are changed and tandem setting of orifices, free from standardization of pipe orifice. Those will be very helpful to pressure reducer, and so forth.

That the C-value of pipe orifice varies with the stations of taps results evidently from the pressure variation on the pipe wall downstream,[8] which fact is supposed to be one of the factors that lead to determining the stations of both taps of present standard orifice.

The stations of taps are different in actuality due to the disparity of the ASME and DIN (German) or JES (Japan) standards as follows:

DIN and JES	Corner taps (directly to orifice plate)
ASME	(*a*) Flange taps (one inch upstream and one inch downstream from orifice plate)
	(*b*) Pipe taps (2.5 *D* upstream and 8 *D* downstream)

The difference between C-values of the ASME standard[9] (flange taps) and those of the corner taps exceed the allowable tolerance of ASME standard (±0.5 per cent) when the Reynolds number R_D is smaller than the values given below depending upon the values of β.

β	0.224	0.448	0.499	0.593	0.633
$R_D \times 10^{-4}$	4	10	15	20	25

The relation between the cavitation coefficient K which Mr. Ball advocates and the authors' cavitation coefficient K_d is expressed as follows:

$$K_d = K\beta^2 \left(\beta^2 + \frac{1}{\beta^2 C^2}\right)$$

Since there is no substantial difference between K and K_d, the authors cannot definitely decide which is more suitable for designing. But usually, H_0, i.e., pressure head one diameter upstream from the orifice plate, is not measured in ASME standard. Cavitation number K containing such value as H_0 (Ref. $H_T = H_0 + (\beta^2 Q/A_0)^2/2g$) is considered as inconvenient for designing.

Mr. Ball says that he thinks the phenomena in K_d = 2.5 to 1.0 are not cavitation but air releasing. According to the information

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[7] K. Stierlin, "Pressure Reducing Plant for a Water Power Station," *Escher Wyss News*, vol. 30, no. 1, 1957.

[8] J. L. Hodgson, "The Measurement of the Flow of Gases and Liquids by Means of Orifices, Nozzles, and Tubes," Proceedings, World Engineering Congress, Tokyo, 1929, vol. IV, p. 111.

F. C. Johansen, "Flow Through Pipe Orifices at Low Reynolds Numbers," Aeronautical Research Committee, Reports and Memoranda, no. 1252, 1929.

[9] R. F. Stearns, R. R. Johnson, R. M. Jackson, and C. A. Larson, "Flow Measurement With Orifice Meters," D. Van Nostrand Company (Canada), Ltd., 1951, p. 222.

recognized recently,[10] cavitation occurrence is regarded as impossible in the absence of nucleus of microscopic air bubble even if in the presence of dissolved air, that is, no cavitation is found in pure vaporization of water. This is different from Mr. Ball's view.

Mr. Ball showed an interest in the audibility of cavitation incipience. Authors adopted three methods for detection of cavitation incipience, that is, (i) by ear, (ii) with the naked eye, (iii) receiving of ultrasonic waves emitted by cavitation.[11] The method (i) is sometimes disturbed by the noise of machinery. The values of K_i for the pipe orifice obtained by three methods agreed with one another. The result concerning method (iii) shall be made public in the near future. In $K_d = 2.5$ to 1.0, ultrasonic wave was received. An ultrasonic shock wave occurs with the collapse of cavitation bubbles, but perhaps not with mere air releasing from water.

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[10] E. N. Harvey, Wm. D. McElroy, and A. H. Whiteley, "On Cavity Formation in Water," *Journal of Applied Physics*, vol. 18, 1947, p. 162.

R. T. Knapp, "Cavitation and Nuclei," TRANS. ASME, vol. 80, 1958, p. 1315.

[11] F. Numachi, "Ultraschallwelle am Tragflügelprofil bei Hohlsog/Teil 1," *Forsch. Ing.-Wes.* vol. 22, 1956, pp. 77–84.

F. Numachi, "Ultraschallwelle am Tragflügelprofil bei Hohlsog/Teil 2," *Forsch. Ing.-Wes.*, vol. 24, 1958, pp. 73–78.

F. Numachi, "Transitional Phenomena in Ultrasonic Shock Waves Emitted by Cavitation on Hydrofoils," JOURNAL OF BASIC ENGINEERING, TRANS. ASME, Series D, vol. 81, 1959, pp. 153–166.