

# HYDRAULICS OF VERTICAL DRAIN AND OVERFLOW PIPES

By A. A. KALINSKE

Assistant Professor of Civil Engineering and Research Engineer  
Iowa Institute of Hydraulic Research

This report covers a series of extensive experiments on the flow of water down vertical pipes which act either as drains or overflows. Keeping in mind practical applications, a drain pipe is one which is connected flush with a horizontal surface such as a roof or the bottom of a tank, and an overflow pipe is one which extends an appreciable distance into a tank or vat. The experimental work was concerned only with the hydraulic and pneumatic conditions when water entered the top of the vertical pipes under such low heads that air was drawn down into the pipes and the pipes did not flow full. The experimental work was conducted on smooth pipes having internal diameters of 0.485, 0.309, and 0.144 ft. Studies were made on 3 or 4 different lengths of each pipe size. An empirical head-discharge relationship was developed which correlated the data reasonably well. The chief effects of varying the length of the pipes were on the value of the critical head which caused the pipe to flow full, and on the amount of air sucked down with the water.

## A. DISCUSSION OF GENERAL PROBLEM

The flow of water down vertical pipes with various types of inlets has been reported in the literature at various times. So-called shaft spillways for dams have been used; a detailed discussion of the design of such a spillway with a widely flared entrance was presented by Kurtz.<sup>1</sup> The so-called "drop-inlet" as applied to soil conservation structures was experimentally studied and reported on by Kessler.<sup>2</sup> The hydraulic and pneumatic phenomena he observed

<sup>1</sup> Kurtz, Ford, "Hydraulic Design of the Shaft Spillway for the Davis Bridge Dam, and Hydraulic Tests of Working Models." *Trans. Amer. Soc. of Civil Engineers*, Vol. 88, p. 1, 1925.

<sup>2</sup> Kessler, L. H., "Experimental Investigation of the Hydraulics of Drop Inlets and Spillways for Erosion Control Structures." *Bulletin University of Wisconsin Engineering Experiment Station* No. 80, 1934.

were generally similar to those observed in the investigations reported herein.

A very careful study of the hydraulics and pneumatics of a small (1-in.) vertical overflow pipe was made by Binnie.<sup>3</sup> Some of his data will be correlated with those obtained in this study on larger sizes of pipes. His description of the manner in which the flow occurs and the accompanying noises is very apt.

In general the flow into and down both overflow and drain pipes, as previously defined, is quite similar. At low heads the flow approaches simple flow over a weir, circular in plan. Of course, the nappe is not aerated which causes a greatly increased flow as compared to simple sharp-crest weir flow. As the water flows down the vertical pipe, which in our investigations was open to the atmosphere at its lower end, large quantities of air are sucked down. The water tends to cling to the sides of the vertical pipe with the air in the center. The water is naturally filled with small bubbles of air but it does not break up into a spray. The maximum velocity of the falling water is reached within a few feet of the entrance; this was discussed in detail in a previous publication on this general problem by Dawson and Kalinske.<sup>4</sup>

The total rate of air flow down the pipe depends on the pipe size, water discharge, and length of pipe. The maximum rate of air flow is obtained at a relatively low water discharge, and this air flow in volume units may be in excess of the water flow. The ability of water flowing down a partly full vertical pipe to suck down a large quantity of air has been put to practical use. A detailed discussion of this is given by Peele<sup>5</sup> in his book on the design of compressed air plants.

The studies described herein were concerned with vertical pipes having square cut edges at the entrance. Such installations of drain and overflow pipes are extremely common for roof rain leaders and tank drains and overflows of various types. The main purpose of the experiments was the developing of a head-discharge relationship and the determination of the effect of pipe length on such a relation-

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<sup>3</sup> Binnie, A. M., "The Use of a Vertical Pipe as an Overflow for a Large Tank." *Proc. Royal Society of London*, Vol. 168-A, p. 219, 1938.

<sup>4</sup> Dawson, F. M. and Kalinske, A. A., "Report on Hydraulics and Pneumatics of Plumbing Drainage Systems." *University of Iowa Studies in Engineering*, Bull. No. 10, 1937.

<sup>5</sup> Peele, R., "Compressed Air Plants," Wiley, p. 248, 1930.

ship. The amount of air drawn down by the flowing water was determined principally as a matter of general interest.

### B. EXPERIMENTAL APPARATUS AND PROCEDURE

The entire experimental apparatus used in these studies is shown in Fig. 1. The first item of importance to note is the water-supply line and the design of the supply tank to insure radial flow into the pipe entrance. The rate of water flow was measured by either a 6" x 3" or 3" x 1½" venturi meter, the size used depending upon the rate of flow. Both meters were calibrated by means of large weighing tanks.

The height of the water in the tank was measured to the nearest thousandth of a foot on a glass manometer which was connected to the false bottom of the tank at several places about 18 in. from the

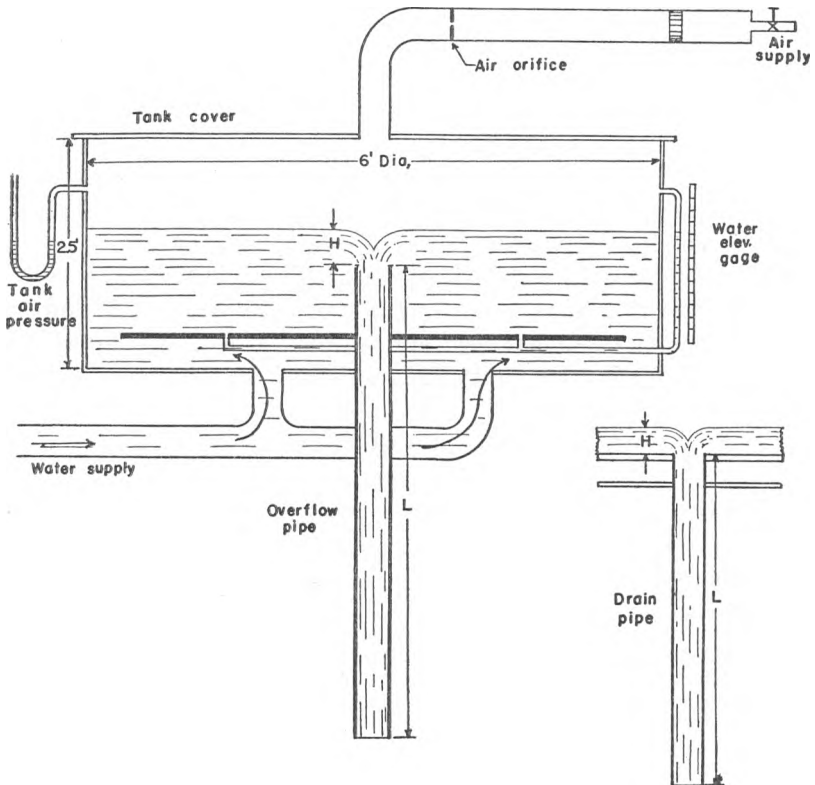


Fig. 1. The experimental apparatus.

center of the pipe entrance. The head  $H$  above the pipe entrance was determined from this reading.

The runs for obtaining data on the head-discharge relationship were taken with the top of the tank completely open to the atmosphere. The experiments were started with the smallest head it was convenient to use and the head was gradually increased until the pipe started to flow full.

The rate of air flow was determined in the following manner: The entire tank was tightly covered and the tank was connected to a separate air-supply line as shown in Fig. 1. The height of water in the tank was read by the same glass manometer as used previously except that the top of the gage was connected to the tank above the water line. A glass U-tube was used to determine the air pressure above the water inside of the tank. After setting a certain rate of water flow, air was supplied to the tank at such a rate as to maintain atmospheric pressure inside of the tank. The rate of air flow was measured by means of a standard orifice located in the air-supply line. The head difference across the orifice was kept below 4 in. of water in order that the thermodynamic corrections would not be necessary in calculating the air flow. This necessitated having a wide range of orifice sizes. This method of determining the air flow was found to be very satisfactory; care, however, had to be taken to maintain the air pressure inside of the tank as close to atmospheric pressure as possible since it was found that the rate of air flow was considerably affected by small pressure differences.

The vertical pipes used were made of transparent "lucite" and had a wall thickness of  $\frac{1}{8}$  in. The transparent pipes were used to permit both visual observation of the flow and the recording on motion picture film of the various interesting phenomena.

### C. RESULTS OBTAINED

Experiments were made on the 0.485 ft., the 0.309 ft., and the 0.144 ft. pipes in that order. Each pipe was first installed as a drain pipe, its top being flush with the tank bottom; then each pipe was installed so that it projected about 10 in. up into the tank, thus acting as an overflow pipe. A few runs were made for each size with the pipe projecting 5 in.; the results were similar to those for the 10 in. overflow. For each size of pipe and for each condition of entrance four different lengths were used, thus making a total of

8 separate test installations for each pipe size, or 24 in all. Sufficient water was not available to obtain heads high enough for the 0.485 ft. pipe to flow full. Therefore, the critical head was not determined for this pipe size.

The head-discharge data obtained are plotted in Figs. 2, 3, 4, 5, 6, and 7. Figs. 2, 4, and 6 show the data when the three pipes were used as overflow pipes, and Figs. 3, 5, and 7 when they were used as drain pipes. The most significant item to note is that all the data for any pipe size and entrance condition tend to fall on one smooth curve for all the pipe lengths as long as the pipe does not flow full. The head at which the pipes begin to flow full was found to depend on their length, the longer the pipe the greater being the head that is necessary above the pipe entrance to cause it to flow full.

The transition from partly full to completely full flow in the pipes is not a very definite phenomenon. After full flow is attained,

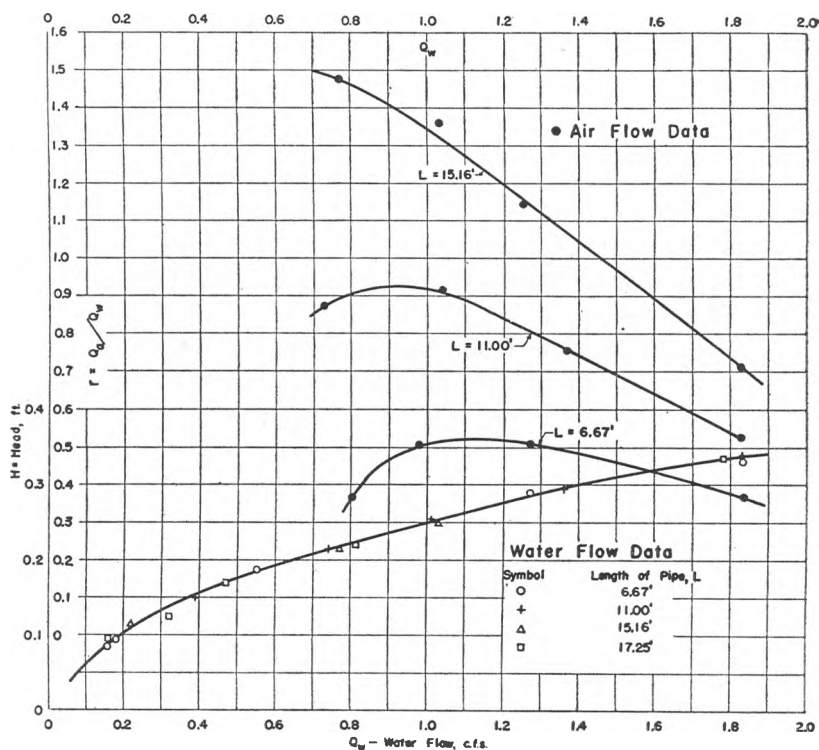


Fig. 2. Water and air flow data for 0.485 ft. overflow pipe.

at the lower heads there is occasional "gulping" of air. As soon as the pipe begins to flow full, any further increase in head above the pipe entrance does not appreciably increase the rate of discharge. In this region the head-discharge relationship is, of course, that for ordinary pipe flow with a sharp-edged or "reentrant" entrance condition.

Another interesting item to note is that for any given head in the region of partly full flow the overflow pipe discharges more water than the drain pipe. The head at which full flow starts for any given length of pipe appears to be slightly larger for the drain pipe — that is, with the end of the pipe even with the bottom of the tank.

The present experimental set-up did not permit longer pipes than those used; however, it would be of interest to obtain further data

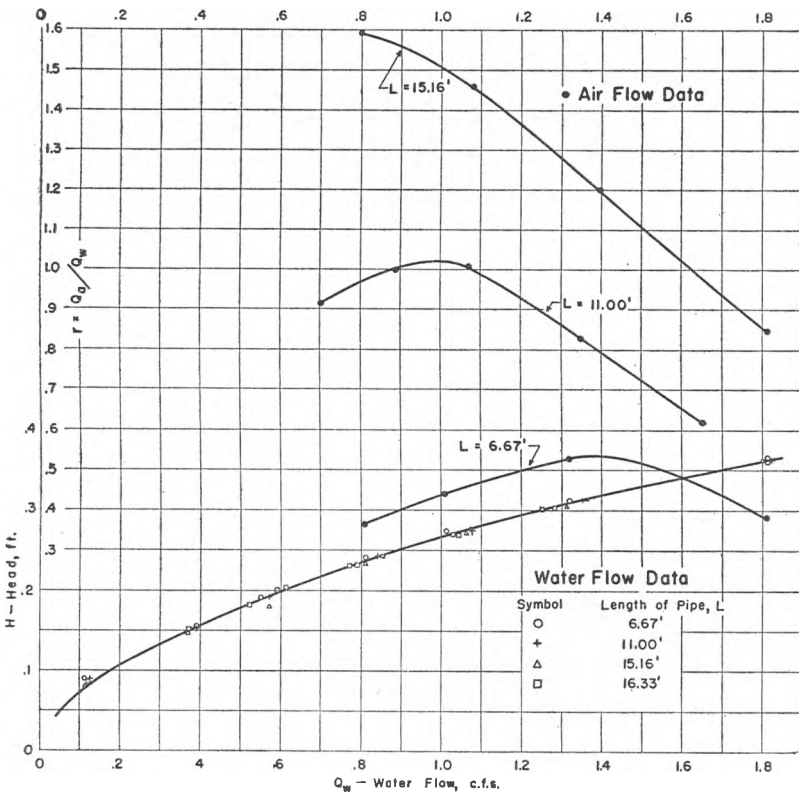


Fig. 3. Water and air flow data for 0.485 ft. drain pipe.

using still longer pipes. Present data indicate that the head-discharge relationship will be independent of pipe length for partly full flow. Also, for very long pipes, it appears that the critical head will tend to attain a fairly constant value.

The ratio,  $r$ , of the rate of air flow  $Q_a$ , to the rate of water flow  $Q_w$ , is also plotted in Figs. 2 to 7 inclusive. Note that a maximum value of  $r$  is reached at a relatively low head. However, the maximum value of  $Q_a$  is attained at a larger head. The rate of air flow tends to increase with the length of the pipe; however, it appears that the increase becomes less with increasing lengths and probably the rate of air flow will tend to attain a constant value for longer pipe lengths. There does not appear to be any significant difference for the air flows between overflow and drain pipes.

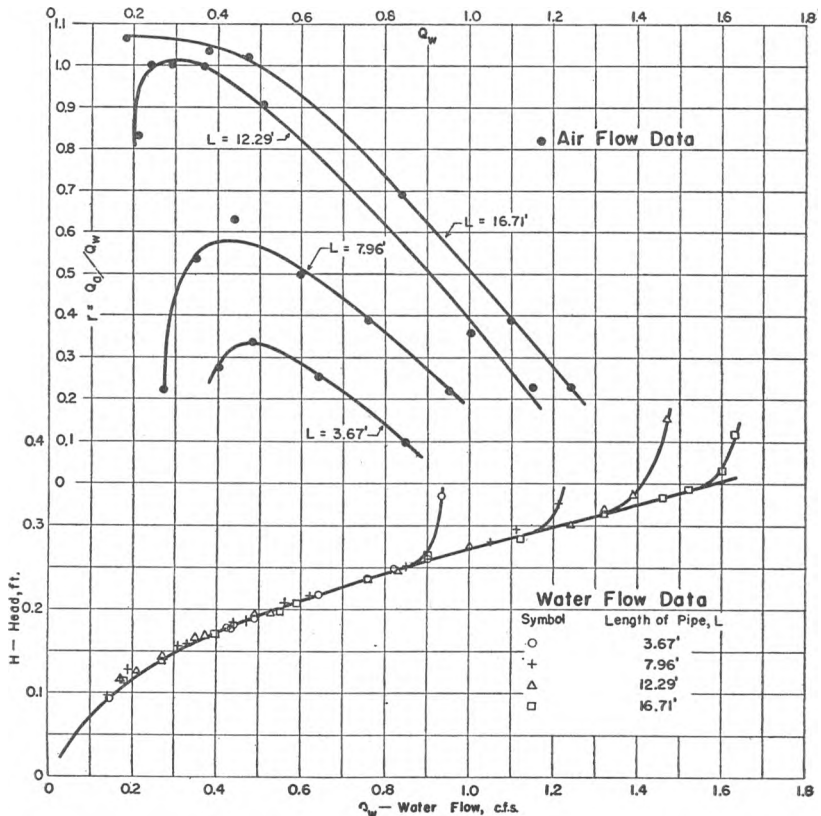


Fig. 4. Water and air flow data for 0.309 ft. overflow pipe.

For pipes about 2 or 3 ft. long, or less, it was possible, if care was used, to obtain perfect orifice flow with a solid jet of water falling straight down without touching the sides of the pipe. The water surface in the tank was perfectly smooth and no vortex tended to form. For longer pipes it was not possible to obtain this condition. The rate of flow under such conditions was considerably less for any given head than for the other type of flow. It seemed that the reason that this jet flow would not occur for long pipes was because the falling jet tended to draw along so much air that a high vacuum occurred near the top of the pipe. This partial vacuum caused the air above the water surface in the tank to push through and break up this jet flow.

For the normal conditions of flow a high vacuum occurred just

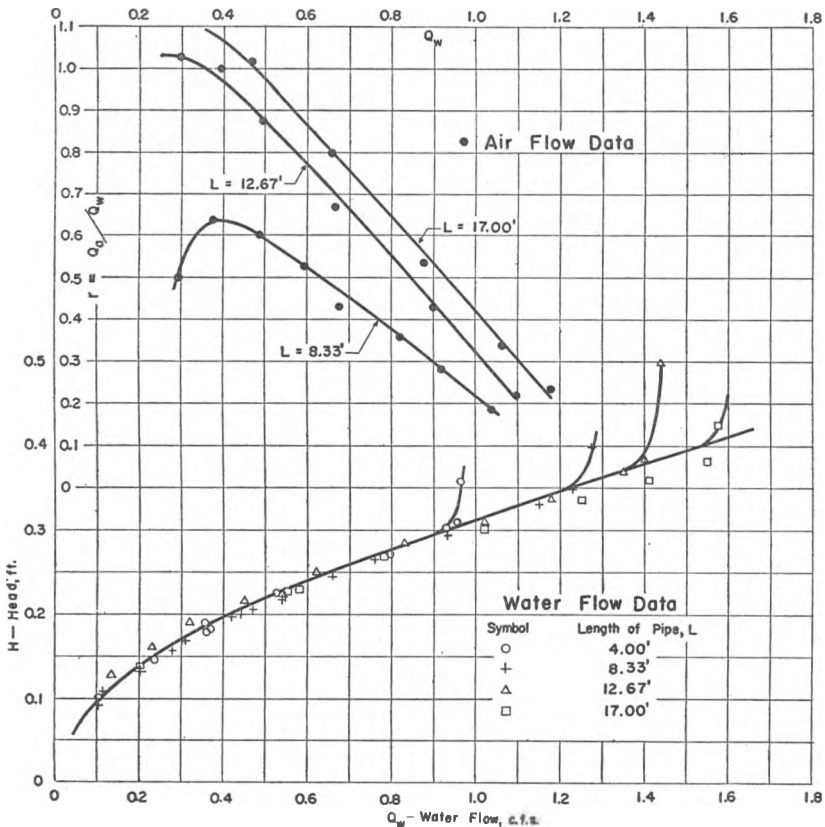


Fig. 5. Water and air flow data for 0.309 ft. drain pipe.



below the entrance, its magnitude increasing with discharge and length of pipe, and for a given discharge being considerably higher for the smaller pipes. For a water flow of just under 2 c.f.s. in the 0.485-ft. pipe a vacuum of 4 in. of mercury was measured for the longest pipe used. For a flow of about 1.3 c.f.s. down the 0.309-ft. pipe when it was 12.67 ft. long a vacuum of 12 in. of mercury was measured. This vacuum below the entrance and its dependence on the discharge, pipe size, and the pipe length had considerable influence on the particular head-discharge relationship obtained.

#### D. ANALYSIS AND CORRELATION OF DATA

It is of considerable interest and of practical usefulness to correlate the head discharge data for the various pipe sizes so as to

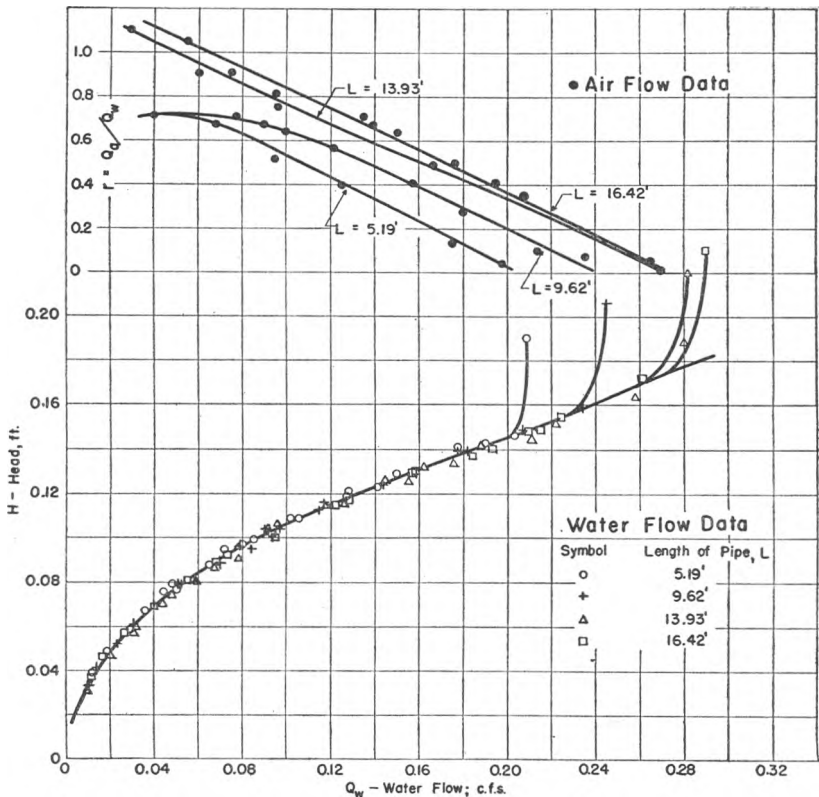


Fig. 6. Water and air flow data for 0.144 ft. overflow pipe.

permit convenient and accurate extension and interpolation of these data for other pipe sizes. Some attempts were made to develop a theoretical relationship; however, nothing useful was obtained. A plotting of the head-discharge data on log-paper indicated that for all the pipe sizes the discharge tended to vary as  $H^2$ . Also, that for a given head, the discharge was proportional to  $D^{1/2}$ , that is, the square root of the pipe diameter.

One might hazard various guesses as to the reason for this particular head-discharge-diameter variation. It is probably tied up with the occurrence of a combination of weir and orifice flow, profoundly affected by the high vacuum formation below the entrance. The vacuum below the entrance undoubtedly causes a tremendous increase in discharge; however, it is peculiar that though longer pipes

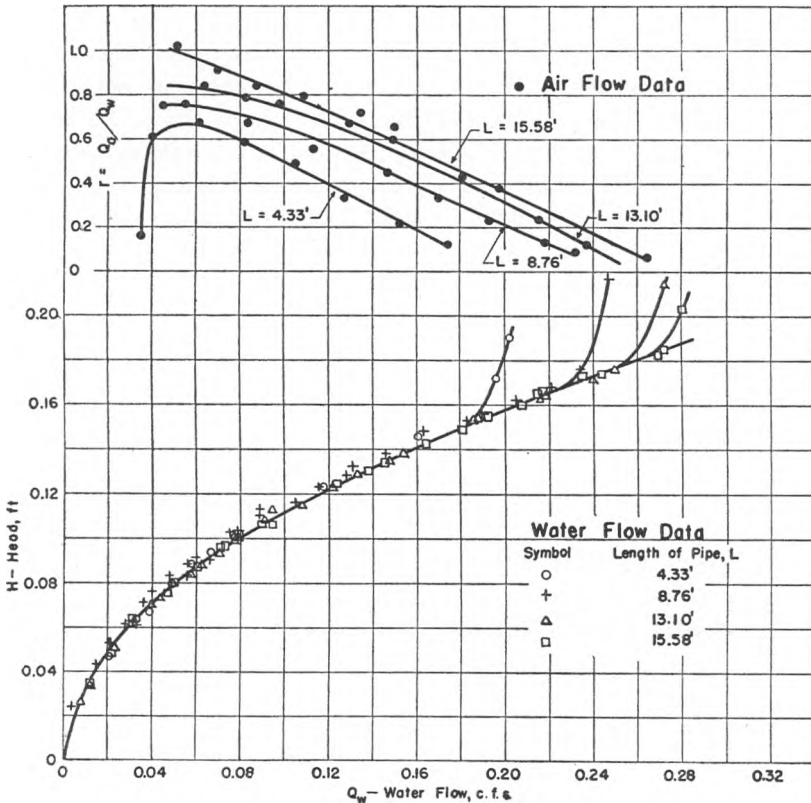


Fig. 7. Water and air flow data for 0.144 ft. drain pipe.

produced a higher vacuum the water discharge was not affected. Instead, the longer pipe and higher vacuum simply caused a higher air inflow.

The relationship that best correlates the data is:

$$Q_w = Cg^{1/2}D^{1/2}H^2 \quad (1)$$

The coefficient  $C$  is dimensionless and thus Eq. (1) can be considered as dimensionally homogeneous. Dimensional analysis indicated that  $C$  ought to depend on the ratio  $H/D$ . In Figs. 8 and 9 values of  $C$  for the various pipe sizes are plotted against  $H/D$  for the overflow and drain pipes respectively. The over-flow pipe values of  $C$  are also plotted for a 1-in. pipe from data obtained by Binnie.<sup>3</sup> Though the data scatter somewhat, it is believed that the variation of  $C$  with  $H/D$  is significant and that Eq. (1) can be used for all practical purposes for calculating flow down overflow and drain pipes installed as described herein. Note that the value of  $C$  for overflow pipes is appreciably larger than for the drain pipes.

It should be pointed out that Eq. (1) is applicable only below the critical head, and therefore the critical head should be known before Eq. (1) can be safely used. An analysis can be made which should give information as to the approximate value of this critical head. When the pipe flows full the total head acting is equal to  $(H + L)$ , where  $L$  is the length of the pipe. The following expressions can then be set up:

$$H + L = C_e V^2/2g + (fL/D)V^2/2g + V^2/2g \quad (2)$$

where  $C_e$  is the entrance loss coefficient and  $f$  is the ordinary pipe friction factor. From Eq. (2) an expression for discharge can be developed:

$$Q = (K\pi D^2/4) \sqrt{2g(H + L)}$$

$$K = 1/\sqrt{C_e + (fL/D) + 1} \quad (3)$$

Graphically, the point where Eq. (3) and Eq. (1) intersect approximates the value of the critical head. On equating these expressions the following relation is obtained:

$$H/D = (K\pi \sqrt{2}/4C_e)^{2/3} (1 + L/H)^{1/3} \quad (4)$$

Therefore, in general the ratio  $H/D$  at the critical head for a given entrance condition is a function of  $L/D$  and  $L/H$ . The coefficients,

<sup>3</sup> Binnie, A. M., "The Use of a Vertical Pipe as an Overflow for a Large Tank." *Proc. Royal Society of London*, vol. 168-A, p. 219, 1938.

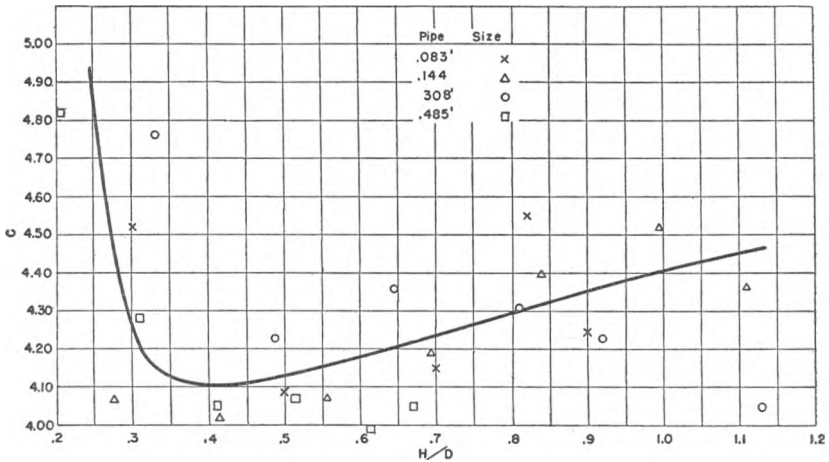


Fig. 8. Variation of water discharge coefficient for overflow pipes.

$C$  and  $f_c$  are assumed constant; actually  $C$  is also dependent on  $L/H$  (See Figs. 8 and 9) and  $f$  varies with pipe roughness, diameter, and velocity of flow. In Eq. (3) the value of  $H$  is small compared to  $L$ ; therefore, neglecting  $H$  would not produce any great error. If now Eq. (3), with  $H$  omitted, and Eq. (1) are equated, the following relation results:

$$H/D = (K\pi \sqrt{2} / 4C)^{1/2} (L/D)^{1/4} \tag{5}$$

This indicates that the critical value of  $H/D$  is approximately a

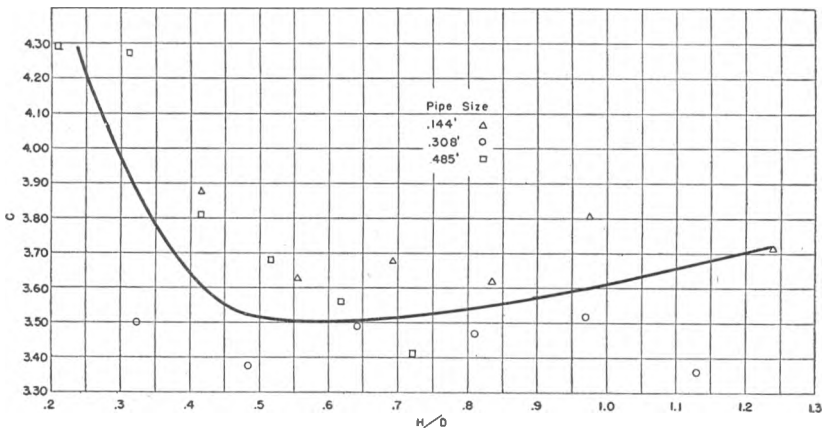


Fig. 9. Variation of water discharge coefficient for drain pipes.

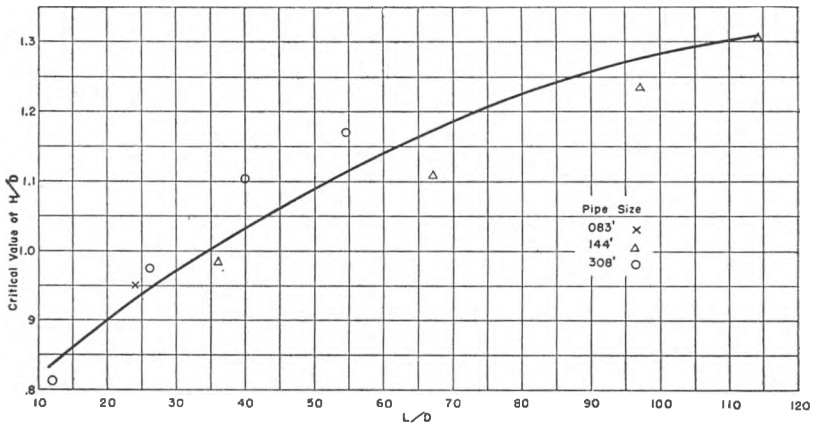


Fig. 10. Variation of critical head for overflow pipes.

function only of  $L/D$ . (It should be noted that  $K$  depends on  $L/D$ ). Eq. (5) permits arriving at an approximate value of  $H/D$ , and then, if desired, a more exact calculation can be made using Eq. (4).

In Figs. 10 and 11 are shown plots of the critical value of  $H/D$  against  $L/D$  for the overflow and drain pipes respectively. The scattering of the points for the different pipe sizes indicates that some other factor is influencing the critical value of  $H/D$ . The factor that varies most for the different sizes of pipe is probably  $f$ , since for smooth pipes  $f$  varies considerably with the pipe diameter and velocity of flow. Another way to look at this problem is that the ratio  $L/D$  indicates geometric similarity and the ratio

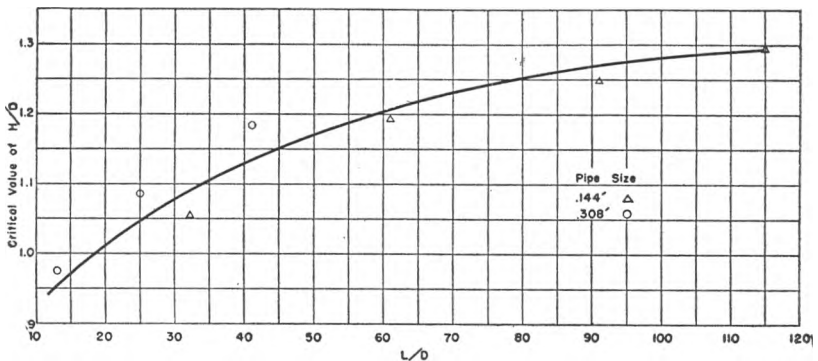


Fig. 11. Variation of critical head for drain pipes.

$H/D$  is proportional to the Froude Number; however, in the plotting of Figs. 10 and 11 the Reynolds number was neglected. Though the Reynolds number does not have much influence when the pipe is not flowing full, it undoubtedly has an appreciable influence when the critical head is approached and the pipe begins to flow full.

Experiments were made to determine the value of the entrance loss coefficient,  $C_e$ , for the case of the pipe flowing full. The value of  $C_e$  for the case of the overflow pipe came out to about 0.70 and for the drain pipe entrance (flush connection) about 0.60. These values can be used for calculating  $\bar{K}$  in Eq. (3). The values of the critical value of  $H/D$  obtained by solving Eq. (5) check the actual experimental values quite well. It is, therefore, suggested that Eq. (5) be used instead of the more complex Eq. (4), which must be solved by trial and error.

#### E. SUMMARY AND CONCLUSIONS

Experimental data on the hydraulics and pneumatics of three sizes of vertical overflow and drain pipes when flowing partly full are presented. The head, which is measured above the top of the pipe, and the water discharge are correlated by a general expression which permits discharge calculations for pipe sizes other than those tested. It was found that the discharge varied as the square root of the pipe diameter and as the square of the head. For flow partly full the head-discharge relationship was independent of the pipe length. For a given pipe size and head the overflow pipe discharged slightly more water than the drain pipe.

The critical head above which the pipe starts to flow full was found to depend on the pipe size, pipe length, and type of entrance. An analysis was made which permitted the prediction of this critical head for any size and length of overflow or drain pipe. The predicted values checked the experimental data quite well.

The ratio of the rate at which air was drawn down with the water, to the water discharge, was a maximum at a relatively low head. The maximum rate of air flow for any given condition occurred at a head considerably less than the critical head. For any pipe size and water discharge the air flow increased with pipe length; however, the increase became less and less for longer pipes, thus indicating that for very long pipes the air inflow would tend to be independent of the pipe length.

## ACKNOWLEDGMENTS

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