ON THE LOSS OF HEAD DUE TO BENDS IN PIPES.

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GENERAL.

In this paper it is proposed to describe and to publish the results obtained in some experiments carried out in the hydraulic laboratory at McGill University in 1898, with a view of determining the loss of head due to sharp bends in pipes. Owing to lack of sufficient leisure time for the work involved in reducing the results, a full account of these experiments has not been previously published.

The experiments were made in drawn copper tubing of about 3-8 inch internal diameter, and the loss of head at the bends was obtained indirectly, by comparing the loss in a pipe with four equal bends with that in a straight pipe of the same bore. The general scheme of the experiments is due to the late Dr. Bovey, then Dean of the Faculty of Applied Science at McGill University, who had had the apparatus prepared for use in the laboratory work in hydraulics; the author takes this opportunity of acknowledging his indebtedness to Professor Bovey for suggesting the experiments and placing the apparatus at his disposal.

It is not proposed to enter into the theory of the flow of water in pipes, and it will be assumed that members are familiar with the usual formulae stating the relations between the quantities concerned, as also with the law that the loss of head per unit length in a straight pipe of uniform section is proportional to the n^{th} power of the velocity, where n is known as the index of roughness, and generally lies between 1.7 and 2.0, the lower values obtaining for smooth pipes and the higher for rough pipes.[1]

A series of experiments was made with each pipe to determine the loss of head at different velocities, the temperature

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(1) Vide Osborne Reynolds. Phil. Trans., Vol. 174.
G, H, Knibbs. Proc, Roy. Soc., N.S.W., Vol. 31.

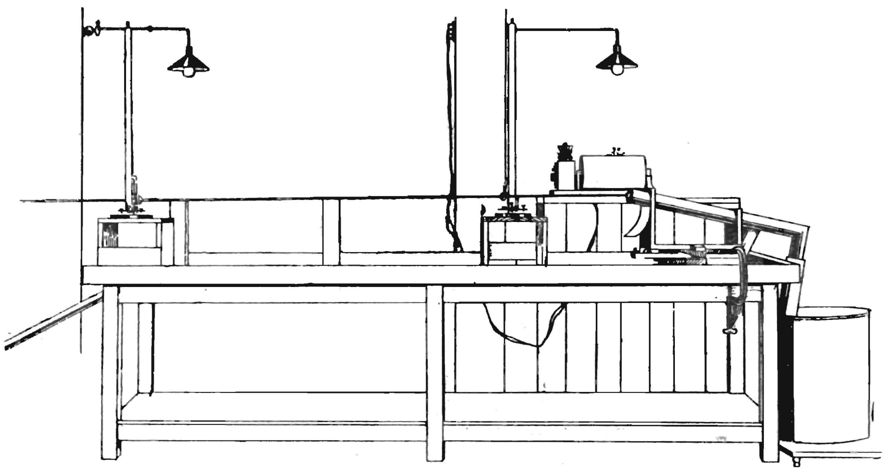
being kept as uniform as possible. From these experiments, a formula, stating the relation between the loss of head and the velocity, was determined for each pipe, and the loss due to the bends then deduced from these formulae.

Each experiment consisted in the measurement of the total quantity of water discharged through the pipe in a measured time, with a constant head of water in the tank from which the supply was drawn: the loss of head was determined by the readings of two mercury columns, which indicated the pressure at each end of the length of pipe under test.

ARRANGEMENT OF APPARATUS.

The general arrangement of the apparatus is shown in the photograph, Plate 1. The experimental tank, from which the

PLATE I.



water was drawn, is to the left, the pipe, gauges, and chute, being supported on a lead-covered bench. The waste water passed through one branch of the chute on to the table, and thence by a waste pipe to a drain in the floor; through the other branch of the chute, the water to be measured was discharged into a calibrated copper vessel, which stood on a plane table on the floor to the right of the photograph. The chronograph which registered the duration of an experiment, is shown beneath the lamp behind the bench.

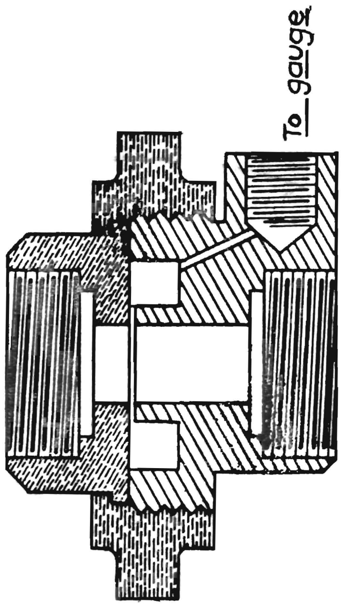
The tank was of cast-iron, perfectly flush inside, 5 feet square in section, and 28 feet high; it has already been fully described before this Society;[2] and in connection with

(2) Vide Strickland. "The Flow of Water through Sharp-edged Orifices." Pro. Sydney Univ. Eng. Soc., 1906.

these experiments, it is merely necessary to state that it was provided with all the apparatus required for properly setting and regulating the head at any desired level up to 20 feet above the level at which the experimental pipe was connected, this level being that of the centre of the orifice plate. The inlet from the main was so arranged, that the disturbance in the main body of water in the tank due to the inflow was reduced to a minimum.

From the tank, the water passed into a four-inch length of ½-inch piping, provided with an ordinary straight-way valve. This pipe was splayed out where it passed through the body of the tank, while to the other end was connected an entrance pipe 32.925 inches long and .375 inch in diameter; the bore of this pipe was enlarged to .53 inch at one end in a distance of about ¼-inch, so that the water should pass into it from the ½-inch pipe without eddy motion. Between this entrance pipe and the length of pipe under test, there was connected what is hereinafter termed a pressure chamber.

PLATE II.



Pressure Chamber

The pressure chamber, which is shown in section in plate 2, not only served to couple together two lengths of piping, but also rendered it possible to obtain the value of the average pressure over the perimeter of the pipe at that point. This is an improvement on the ordinary piezometer connection, which gives the pressure at one to four points on the perimeter. The pressure chamber consists of three parts, two into which the lengths of piping to be coupled are screwed, and a third coupling the other two. There is a continuous opening less than one two-hundredth of an inch wide around the bore, opening into a chamber from which a connection is made to the pressure gauge by means of rubber tubing. The distance between the opening and the ends of the experimental length was .1875 inch in each chamber, so that it is necessary to add twice that length, or .375 inch, to the measured length of the pipe under test in order to obtain the length over which the loss of head was measured. The internal diameters of the bores of the pressure chambers were .3798 inches for that at the upstream end, and .3818 inches for that at the down-stream end of the experimental pipe; but no correction has been applied to cover the small loss of head due to the change in diameter from the pressure chambers to the main pipe, as it was considered that the correction would not materially affect the results.[3]

The experimental lengths of piping were fitted at each end with a head having a screw thread and a carefully turned face, which fitted into the pressure chamber.

Beyond the down-stream pressure chamber there was connected a length of pipe .3717 of an inch in diameter and 24.035 inches long, from which the water was discharged into a bifurcated chute.

This chute consisted of two lengths of galvanized iron piping, fitted side by side, and supported on a wooden frame so pivoted that the chute could be turned rapidly through a small angle, so as to receive the water discharged from the pipe, and pass it through one branch to the copper measure, or when in the other position, through the second branch to waste; the instant at which the change was made from one position to the other was recorded on the chronograph.

The chronograph was connected to a standard clock in the adjacent Testing Laboratory, a mark being made every second:

(3) As a matter of fact the correction to be applied is somewhat uncertain. For an enlargement of section the loss of head is generally taken as being $m \frac{v^2}{2g}$ where $m = \left(\frac{A_2}{A_1} - 1\right)^2$; in the case under consideration $\frac{m}{2g} = .0004$ for the case of the straight pipe; the loss due to a diminution of section is generally assumed to be $.316 \frac{v^2}{2g} = .0049\ v^2$ which is evidently of mportance. This value is, however, derived from a consideration of the loss occurring at the junction of a pipe with a tank or reservoir, and being due to the contraction of area of the jet would not apply to a case where the full contraction does not occur. Assuming that the loss at the point of contraction is 50 per cent. greater than at the point of enlargement, the total loss of head due to the two changes in section would be $.001\ v^2$. The error would be less in the case of three of the pipes, and as only the difference enters into the final result the error may be neglected.

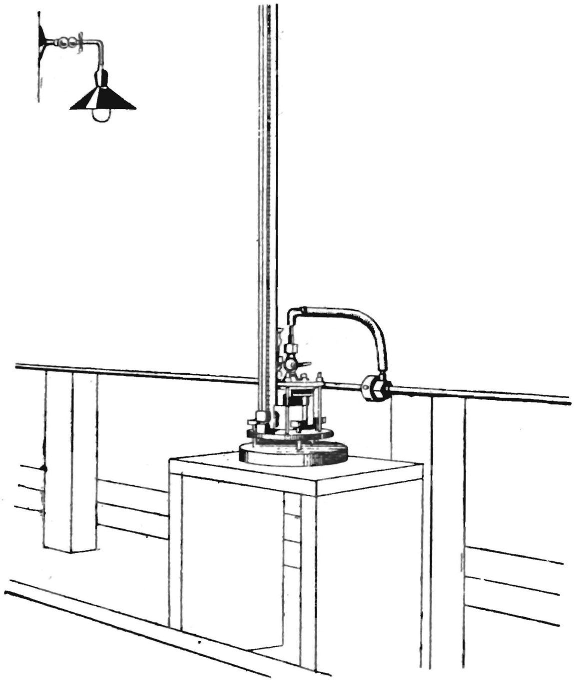
the distance in the record corresponding to one second was 0.40 of an inch, though this could be doubled if greater accuracy was required. The special feature of the chronograph, viz., the use of two pens, has been previously described before this Society.[4] A stop-watch was also used as a safeguard against large errors, and also to indicate the elapsed time during an experiment.

The quantity of water discharged during a run was measured in a cylindrical copper vessel, which stood on a levelled plane table by the end of the bench. This measure was calibrated in gallons, and was fitted with a vertical gauge glass, with a steel scale beside it divided into hundredths of an inch. This scale was read through a Marten's telescope, placed on a stand about 6 feet from the measure, the cross wire being set on the bottom of the meniscus, and then read on the scale.

It should be stated that the lengths of piping were accurately levelled.

The gauges used for registering the pressure of the water in the pipes, were of a special pattern (see Plate III). The base

PLATE III.



(4) See Footnote (2).

of the gauge is an iron plate about 3-8in. thick, provided with three brass levelling screws. On a ring of india-rubber on the plate stands a cylindrical glass vessel, or reservoir, about 2½ inches in diameter, with an aluminium cover. Four rods, screwed into the base plate and passing through the cover, have screwed ends and nuts at the top, by which the reservoir is pressed down on the rubber ring. In the centre of the aluminium top is a tap and nipple into which is screwed a T-piece, the upper part of which is provided with an air-cock, while the horizontal branch is connected with the pressure chamber by means of a piece of rubber tubing. Beneath the iron base is a pipe connecting the reservoir with a vertical glass tube of 5-16-inch bore and 35 inches in length. Behind this tube is a scale reading up to 32 inches and movable relatively to the tube and reservoir. At the lower end of the scale, a spindle is attached to the back and passes through a gland into the reservoir. The bottom of this spindle is of aluminium, with a point on the same level as the zero of the scale. On the top of the spindle is a milled head, by means of which the spindle and scale can be moved up or down until the point touches the surface of the mercury in the reservoir. The reading of the scale is then evidently the height of the mercury column above the level of the mercury in the reservoir. There is a small steel auxiliary scale, with .01-inch divisions, which measures the displacement, from a datum, of the zero of the main scale, when the latter is moved until the point touches the surface of the mercury. The zeros of the small auxiliary scales of the two gauges were set to the same level every morning in the manner hereinafter described. It is easily seen that the displacement of the main scale, or rather the difference of the displacements of the two scales from the same level, is a correction in pressure of water to be applied to the difference of the readings of the mercury columns.

As the graduation of the scales supplied with the gauges was unsatisfactory, steel scales accurately graduated to hundredths of an inch were securely fixed to them, with their zeros set on the same level as the surface of the mercury in the tubes when the pointers were touching the surface of the mercury in the reservoirs before water was admitted.

A trial was made of an arrangement for determining the position of contact electrically instead of by sight, but the results were unsatisfactory and a number of experiments, in which this method had been used had to be rejected. The most accurate method would no doubt be to use a hook gauge instead of the blunt pointer as described; although it is considered that the error in any case is very small. This pattern of gauge could also be improved by having a larger reservoir and better facilities of draining and cleaning.

Each scale was read by a Marten's telescope fixed on a stand about 12 feet in front of the gauge, and adjusted to approximately the level of the top of the mercury column.

The five pipes on which experiments were made, are shown diagrammatically in plate 4, on which are also given the

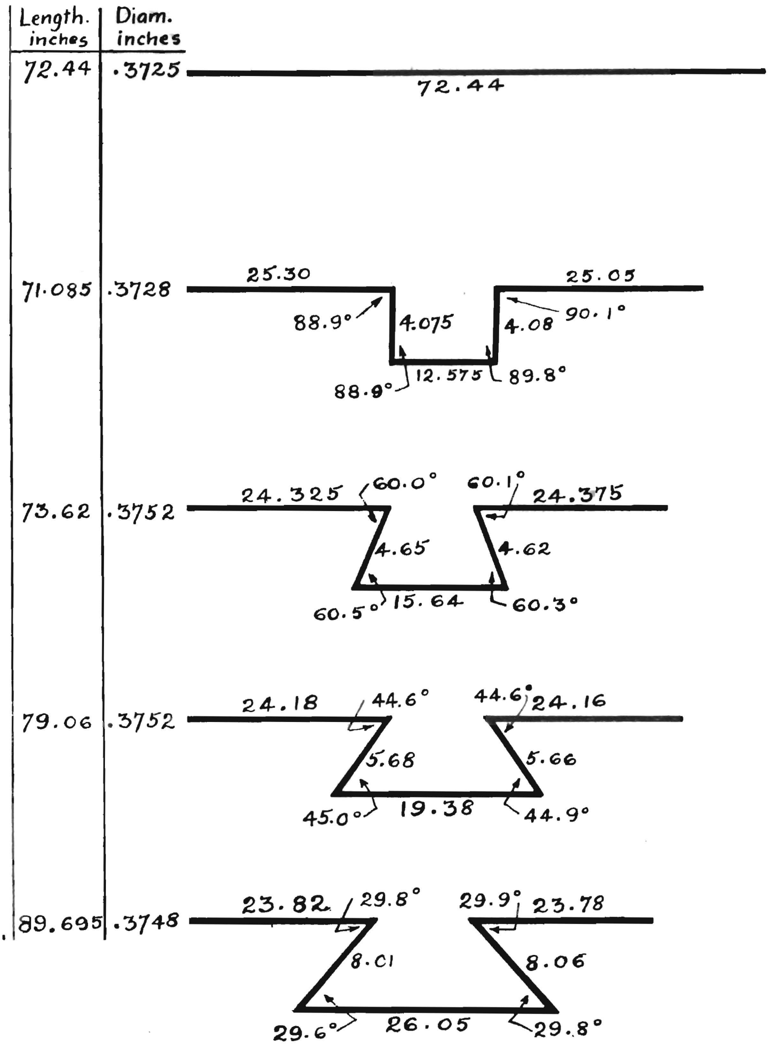


FIG. 4.

lengths and diameters: as noted before, .375 of an inch must be added to the lengths as given, in order to obtain the lengths over which the loss of head was determined. The measuring of the length was, of course, simple in the case of the straight pipe, but it was difficult to obtain the length of the axis in the bent pipes; judging, however, by the agreement in the values deduced for the internal diameters, the values of the lengths were obtained fairly accurately, the probable error having been reduced by taking a number of different masurements.

The diameters were determined by weighing the pipes when empty and when full of water. Owing to the lengths of the pipes, the weighing could not be carried out on an ordinary balance, and it was therefore necessary to use the impact balance in the hydraulic laboratory. A description of this balance does not come within the scope of this paper.[5] Suffice it to say that it was sufficiently sensitive to respond to the addition of a single drop of water, which is a minute fraction of the weight of water contained in the shortest pipe, viz., .2848 of a lb. A special stopper was made to screw on to the lower end of the pipe, forming a flush water-tight joint; the top end was left open. The pipes were filled and hung on the balance for a day before the weighing, care being taken to remove air bubbles by tapping. The temperature of the water was measured immediately after weighing and varied from 68deg. F., to 73deg. F., for the different tubes. The tubes were measured at temperatures varying from 62deg. to 65deg. F., but no correction has been applied on account of the slight expansion to the temperature at which they were weighed. In calculating the diameters the values of the density of water were taken from the table given in the article on "Hydromechanics," in the Encyclopaedia Britannica. It should be stated that determinations of the density of several samples showed that the water did not differ materially in density from pure water.

It will be noticed that the pipes are divided by differences in diameter into two sets, those having the smaller diameter were of plain copper, while the others were nickel-plated outside.

EXPERIMENTAL WORK.

In the first experiments made, which were those at the highest velocities obtainable, the inlet valve between the tank and pipe was fully open and the head was regulated by adjusting the level of water in the tank; under these conditions, the mercury columns were perfectly steady. When, for later experiments at the lower velocities, the head in the tank was reduced to about 10 feet, oscillations were observable in the mercury column nearer the tank, and these oscillations increased as the head was lowered. The pipe inlet valve was then partly closed, and the head in the tank raised, and this had the desired effect of

(5) Vide Bovey and Farmer, Trans. Can. Soc. C.E., May, 1898.

greatly diminishing and generally of totally removing the disturbance, so that for the lower velocities, this method was generally adopted. The length of pipe between the valve and the first gauge was considered sufficient to ensure that all disturbance due to throttling, had been eliminated at the pressure chamber; the uniformity of the results indicates that such was the case.

It was found necessary to clean out the reservoirs of the gauges every morning, as during the night sediment was deposited on the surface of the mercury, preventing the accurate setting of the index. The mercury was removed, cleaned, and filtered occasionally when it appeared necessary.

The zeros of the gauges were set in the same horizontal plane every morning, the datum plane generally taken being that passing through the centre of the orifice and through the centre line of the pipe, where it entered the tank. This setting was effected as follows:—The pressure in inches of mercury corresponding to the head of water in the tank was calculated (the density of mercury being taken throughout at 13.6). The gauges were then raised or lowered by the levelling screws to give this reading when the pointers were touching the surfaces of the mercury in the reservoirs. The small auxiliary scales were then adjusted to the zero, and the subsequent movement of the main scales from the initial position could then be observed on the auxiliary scales. This method is open to some objection, as its accuracy depends upon the equality of the bores of the two glass tubes of the gauges: these were nominally of the same diameter, and as there was no difference apparent, it is thought that no serious error has been introduced by assuming that the depth of the meniscus would be the same in each tube.

After the gauges had been cleaned and adjusted, the water was turned on, and the head in the tank raised or lowered, or the throttle valve regulated until the required difference of level in the mercury columns had been obtained. The inlet and escape valves of the tank were then regulated so as to maintain a constant head in the tank, the valve at the inlet to the pipe being left in the same position throughout the experiments at the one velocity. The chronograph was then started, the temperature of the water flowing from the pipe taken, and the chute thrown over to discharge the water into the measure. The gauges were then set and read, and if time permitted, second and third settings and readings were made, the temperature at the inlet being taken after each reading. The head of water in the tank was observed at frequent intervals, in order to detect any tendency to variation, which, if noticeable, was checked at once by regulating the overflow valve. When a sufficient quantity of water had been discharged into the measure, the chute was thrown over, the chronograph stopped, and the measure read and checked. The measure was then emptied, drained, and replaced on the stand, and a second run was made under the same conditions. This was generally followed by a third, and if any disagreement was noticed, by a fourth experiment. A stop-watch was used as a check against large errors in the reading of the chronograph, the latter being used principally to give the fractions of a second. The times of the separate runs at the same head were generally kept approximately the same, and thus, any large error in the first reading of the measure could be noticed and corrected at once. For similar reasons, the quantity of water discharged during a run was kept about the same throughout the experiments.

The following symbols are used throughout the paper:—

v=the mean velocity of the water in the pipe in feet per second.

w=the rate of discharge in gallons per second.

d=the diameter in inches.

l=the distance between piezometers in feet.

h=the difference of pressures at the piezometers in feet of water.

t=the temperature in degrees Fahrenheit.

f=the relative fluidity.

n=the index of roughness.

s=the equivalent slope $= \frac{h}{l}$

λ=the loss of head due to one bend in feet of water.

k=a constant defined below.

In the text and tables, log h., log l., etc., are abbreviated $\dot{h}$, $\dot{l}$, and so on.

The expression used as a basis of the calculations, is of the form propounded by Osborne Reynolds,[6] as subsequently modified by G. H. Knibbs,[6] viz.:—

$$v^n = a f^{\frac{q}{n}} d^{\frac{m}{n}} \frac{h}{l}$$

which for any one pipe at constant temperature, may be written:—

$$\frac{h}{l} = k w^n$$

It is desirable to indicate the magnitude of the probable errors in the measurement of the various quantities involved.

The measure had a total capacity of 20 gallons, and the quantity discharged was in almost every case between 14 and

(6) See Note 1, (6) See Note 1.

15 gallons; the length on the scale corresponding to 1 gallon was 0.88 of an inch, and the reading was always taken to one thousandth of an inch, which corresponded to 0.001136 of a gallon, or 1 in 12,500. It is not pretended that this degree of accuracy was reached, but it is fair to assume that the relative error would not exceed 1 in 5000. The measure was always carefully drained after each run, and always filled and drained before the first run in the morning. The temperature of the water contained in the measure was always taken when the measure was read, but, as it seldom differed by more than a tenth of a degree Fahrenheit from that of the water as it emerged from the pipe, no correction has been applied on this account. The author cannot vouch personally for the accuracy of the calibration of the measure, as the laboratory calibration was accepted, and any error in this would merely effect the absolute and not the relative results. It should here be stated that the gallon was taken to be equal to .16037 of a cubic foot.

The total time varied from 150 seconds in the experiments at high velocities, up to 1100 seconds for those at the low velocities. On the chronographic record, 0.40 of an inch corresponded to one second; the record was read to one hundredth of an inch, corresponding to 1 in 6000 in the worst case. With all allowance for inaccuracies, the error would hardly exceed 1 in 3000. No record was kept of the rate of the clock, but it was checked daily by signal from the McGill Obsrvatory, and was regulated as found necessary, and it is known that there is no appreciable error in this connection.

In obtaining the value of the loss of head, there are several sources of error, in addition to the reading of the height of the mercury column, viz., the setting of the zeros of the scales on the same level, the adjustment of the pointers to touch the surface of the mercury in the reservoirs, and the value of the density of the mercury. The height of the mercury columns in the gauges was read to .001 of an inch, and including the error in setting the zero, the probable error in any one reading should not have exceeded .003 of an inch. As, however, the difference between the readings of the two colmuns and not the absolute height is being obtained, any constant error would be eliminated as well as most of the error due to personal equation; such as that in estimating the tenth part of the interval between graduation marks on the scale. It should be stated that, with a good light, the definition of the top of the mercury column, as seen through the telescopes, was very exact, and the lines on the scale very sharp; while the mercury columns were generally free from oscillation. It may, therefore, be assumed that the value of the difference in head was determined to within .0025 of an inch of mercury. The least difference was about .715 of an inch, so that the maximum error should not exceed 1 in 300.