(Art. 26) As an illustration of $(26)_2$ let water issue from a pipe 6 centimeters in diameter with a velocity of 4 meters per second. The cross-section is found from Table F to be 0.002827 square meters, and then the theoretic work in kilogram-meters per second is

$$K = 0.05102 \times 1000 \times 0.002827 \times 4^3 = 9.23$$

which is 0.123 metric horse-power. If the velocity is 16 meters per second, the stream will furnish 7.87 horse-powers.

(Art. 30) The area $a$ is in square meters, the velocity $V$ in meters per second, and the discharge $Q$ in cubic meters per second. Thus if a pipe 20 centimeters in diameter discharges 0.15 cubic meters per second, the area of the cross-section is 0.03142 square meters and the mean velocity is $0.15/0.03142 = 4.77$ meters per second.

(Art. 31) In Fig. 31*a*, suppose the sections $a_1$ and $a_2$ to be 0.06 and 0.12 square meters, and the depths of their centers below the water level of the reservoir to be 4.5 and 5.5 meters. Let 0.24 cubic meters per second be discharged from the pipe, then from $(31)_1$ the mean velocities in $a_1$ and $a_2$ are 4.0 and 2.0 meters per second. The velocity-heads are then 0.82 meters for $a_1$ and 0.20 meters for $a_2$, so that during the flow the pressure-head at $A$ is $4.5 - 0.82 = 3.68$ meters and that at $B$ is $5.5 - 0.20 = 5.30$ meters.

Prob. 33*a*. What theoretic velocities are produced by heads of 0.1, 0.01, and 0.001 meter? What is the velocity-head of a jet, 7.5 centimeters in diameter, which discharges 500 liters per second?

Prob. 33*b*. A prismatic vessel has a cross-section of 1.5 square meters and an orifice in its base has an area of 150 square centimeters. Compute the theoretic time for the water level to drop 3 meters when the head at the beginning is 4 meters.

Prob. 33*c*. A small turbine wheel using 3 cubic meters of water per minute under a head of $10\frac{1}{2}$ meters is found to deliver 5.1 metric horse-powers. Compute the efficiency of the wheel.

Prob. 33*d*. In an inclined tube there are two sections of diameters 10 and 20 centimeters, the second section being 1.536 meters higher than the first. The velocity in the first section is 6 meters per second and the pressure-head is 7.045 meters. Find the pressure-head for the second section.



# CHAPTER 4

## INSTRUMENTS AND OBSERVATIONS

### Art. 34. General Considerations

Some of the most important practical problems of Hydraulics are those involving the measurement of the amount of water discharged in one second from an orifice, pipe, or conduit under given conditions. The theoretic formulas of the last chapter furnish the basis of most of these methods, and in the chapters following this one are given coefficients derived from experience which enable those formulas to be applied to practical conditions. These coefficients have been determined by measuring heads, pressures, or velocities with certain instruments, and also the amount of water actually discharged, and then comparing the theoretic results with the actual ones. It is the main object of this chapter to describe the instruments used for this purpose, and a few remarks concerning advantageous methods for the discussion of the observations will also be made.

The engineer's steel tape, level, and transit are indispensable tools in many practical hydraulic problems. For example, two reservoirs $M$ and $N$, connected by a pipe line, may be several miles apart. To ascertain the difference in elevation of their water surfaces lines of levels may be run and bench marks established near each reservoir, as also at other points along the pipe line. From the bench marks at the reservoirs there can be set up simple board gages, so that simultaneous readings can be taken at any time to find the difference in elevation. From the bench marks along the pipe line a profile of the same can be plotted for use in the discussion. With the transit

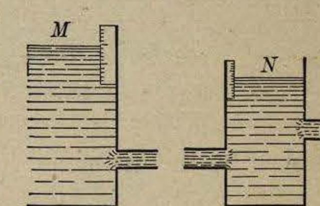

Fig. 34*a*.

and tape the alignment of the pipe line and the lengths of its curves and tangents can also be taken and mapped. All of these records, in fact, are necessary in order to determine the amount of water delivered through the pipe.

For work on a smaller scale, like that of the discharge from an orifice in a tank, the steel tape may be used to mark points from which a glass gage tube may be set and upon which the height of the water surface above the orifice can be read at any time during the experiment. Another method is to have a float on the water surface, the vertical motion of which is communicated to a cord passing over a pulley, so that readings can be taken on a scale as the weight at the lower end of the cord moves up or down. When the head is very small, however, these methods are not sufficiently precise, and the hook gage described in Art. 35 must be used.

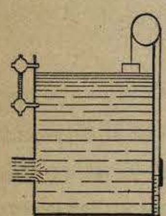
Fig. 34*b*.

It is often desirable for many purposes to keep a continuous record of the level of a water surface. This can be accomplished by the use of an automatic recording gage such as that shown in Fig. 34*c*. This apparatus, as made by Freiz, consists essentially of a float connected to a flat perforated copper band which passes over a sprocket wheel and

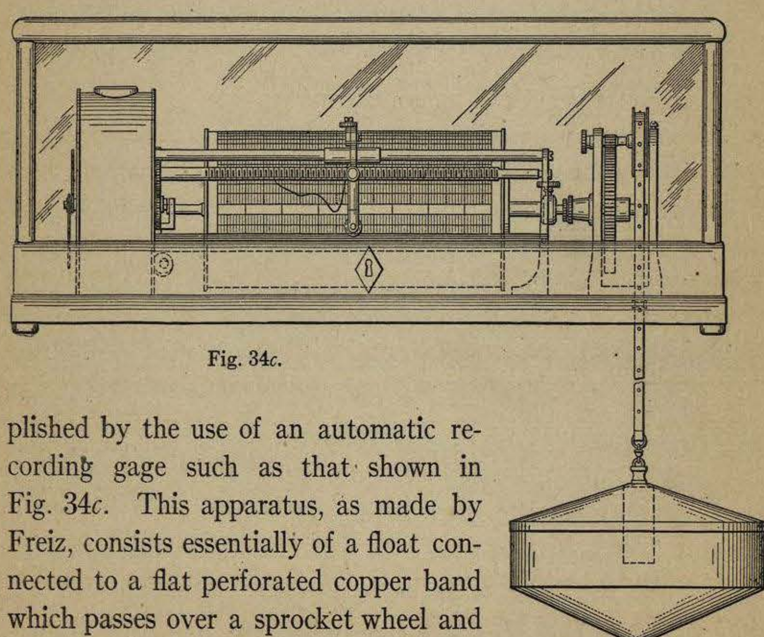
Fig. 34*c*.



which carries at its other end a counterweight. The sprocket wheel is directly connected to a drum the circumference of which is exactly one foot and on which a sheet of ruled paper can be clamped. A clockwork moves a pen at a constant and uniform rate in a direction parallel to the axis of the cylinder, and if the latter remains stationary, the pen will draw a straight line on the paper. If, however, the cylinder is caused to revolve by the rising or falling of the float, the pen will draw a curve, and each revolution of the cylinder will represent a change of one foot in the water level. Each sheet or chart, depending on the gear of the clock, will give a record either 24 hours or 7 days long before a new chart must be put on by an attendant. By the interposition of suitable gears between the sprocket wheel and the cylinder the ratio of the number of revolutions between the sprocket and the drum can be fixed at any desired number. With all forms of apparatus of this kind it is desirable that the float should be of large horizontal diameter in order that its lifting power may be sufficient to overcome the friction in the bearings of the machine and so cause it to easily and quickly respond to small fluctuations in the water surface.

The Bristol recording water level gage operates on the principle of the aneroid barometer. A bronze cylindrical box encloses air, the pressure of which is communicated through a flexible tube to the recording apparatus whenever that pressure exceeds the exterior atmospheric pressure. When this box is placed under water, the head of water acts on a diaphragm and increases the air pressure an amount proportional to the head on the diaphragm. In the recording apparatus is a pen which draws a curve on a sheet of paper moved by clockwork and thus gives a continuous record of the water level. This apparatus has been used for recording the heights of tides and of water levels in reservoirs. Of course the adjustment of the instrument must be made by experiment, its record being compared by one made by direct methods. The closest reliable reading of a gage of this kind appears to be about one-eighth of an inch.

A small quantity of water flowing from an orifice may be measured by allowing it to run into a barrel set upon a platform weighing scale. The weight of water discharged in a given time is thus ascertained, the time being noted by a stop-watch, and the volume is then computed by the help of Table 3. If the flow is uniform, the discharge in one second is then found by dividing the volume by the number of seconds. A larger quantity of water may be measured in a rectangular tank, the cross-section of which is accurately known; here the water surface is noted at the beginning and end of the experiment, and the volume is then computed by multiplying the area by the differences of the two elevations. For example, a square tank was 4 feet 2 inches inside dimensions, and the gage read 3.17 feet at the beginning and 4.62 feet at the end of the experiment, which lasted 304 seconds; then the flow, if uniform, was 0.0828 cubic feet per second.

Larger quantities of water still are sometimes measured in the reservoir of a city supply. The engineer, by the use of his level, transit, and tape, makes a precise contour map of the reservoir, determines with the planimeter the area enclosed by each contour curve, and computes the volume included between successive contour planes. For instance, if the area of the contour curve $AB$ is 84 320 square feet and that of $CD$ is 79 624 square feet and the vertical distance between the contour planes is 5 feet, the volume included is 409 860 cubic feet by the method of mean areas. A more precise determination, however, may be made by measuring the area of a contour curve halfway between $AB$ and $AC$; if this is found to be 82 150 square feet, the volume included between $AB$ and $AC$ is computed by the prismoidal formula and found to be 410 450 cubic feet.

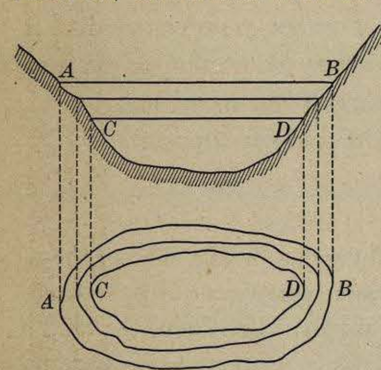

Fig. 34*d*.

These direct methods of water measurement form the basis of all hydraulic practice. In this manner water meters are rated, and the coefficients determined by which practical formulas for flow through orifices, weirs, and pipes are established. These coefficients being known, indirect methods may be used for water measurement; namely,



the discharge can be computed from the formulas after area and heads have been ascertained. There are also methods of indirect measurement from observed velocities which will be described later, and which are especially valuable in finding the discharge of conduits and streams.

Prob. 34. Water flows from an orifice uniformly for 89.3 seconds and falls into a barrel on a platform weighing scale. The weight of the empty barrel is 27 pounds and that of the barrel and water is 276 pounds. What is the discharge of the orifice in gallons per minute, when the temperature of the water is 62° Fahrenheit?

## Art. 35. The Hook Gage

The hook gage, invented by Boyden about 1840, consists of a graduated metallic rod sliding vertically in fixed supports, upon which is a vernier by which readings can be taken to thousandths of a foot. At the lower end of the rod is a sharp-pointed hook, which is raised or lowered until its point is at the water level. Fig. 35*a* represents the form of hook gage made by Gurley, the graduation on the rod being to feet and hundredths. The graduation has a length of 2.2 feet, so that variations in the water level of less than this amount can be measured, by using the vernier, to thousandths of a foot. To take a reading on a water surface, the point of the hook is lowered below the surface and then slowly raised by the screw at the top of the instrument. Just before the point of the hook pierces the skin of the water (Art. 2) a pimple or protuberance is seen to rise above it; the hook is then depressed until the pimple is barely visible and the vernier is read. The most precise hook gages read to ten-thousandths of a foot, and it has been stated that an experienced observer can, in a favorable light and on a water surface perfectly quiet, detect differences of level as small as 0.0002 feet.


Fig. 35*a*.

A cheaper form of hook gage, and one sufficiently precise for many classes of work, can be made by screwing a hook into the foot of an engineer's leveling rod. The back part of the rod is then held in a vertical position by two clamps on fixed supports, while the front part is free to slide. It is easy to arrange a slow-motion movement so that the point of the hook may be precisely placed at the water level. The reading of the vernier is determined when the point of the hook is at a known elevation above an orifice or the crest of a weir, and by subtracting from this the subsequent readings the heads of water are known. A New York leveling rod, reading to thousandths of a foot on its vernier, is to be preferred for this work.

Hook gages are principally used for determining the elevations of the water surface above the crest of a weir, as the heads of water are small and must be known with precision. In Fig. 35*b*, the crest of the weir is seen and the hook gage is erected at some distance back from it, where the water surface is level. In this case great care should be taken to determine the reading corresponding to the level of the crest. In the larger forms of hooks this may be done by taking elevations of the crest and of the point of the hook by means of an engineer's level and a light rod. With smaller hooks it may be done by having a stiff permanent hook, the elevation of whose point with respect to the crest is determined by precise levels; the water is then allowed to rise slowly until it reaches the point of this stiff hook, when readings of the vernier of the lighter hook are taken. Another method is to allow a small depth of water to flow over the crest and to take readings of the hook, while at the same time the depth on the crest is measured by a finely graduated scale. Still another way is to allow the water to rise slowly, and to set the hook at the water level when the first filaments pass over the crest; this method is not a very precise one on account of capillary attraction along the crest. As the error in setting the hook is a constant one which affects all the subsequent observations, especial care should be taken to reduce it to a minimum by taking a number of observations in order to obtain a precise mean result.

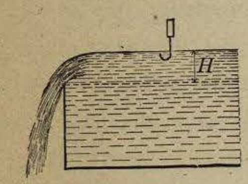


Fig. 35*b*.

The hook gage is also used to find the difference of the water levels in tanks for experiments for the determination of hydraulic



coefficients, and in wells along pipe lines when experiments are made to investigate frictional resistances. In general its use is confined to cases where the head is small, as for high heads so great a degree of precision is not required (Art. 54).

Prob. 35. A wooden tank, 4.52 by 5.78 feet in inside dimensions, has leakage near its base. The hook gage reads 2.047 feet at 11.57 A.M., 1.470 feet at 12.05 P.M., and 0.938 foot at 12.13 P.M. Compute the probable leakage in the first and last minutes.

## Art. 36. Pressure Gages

A pressure gage, often called a piezometer, is an instrument for measuring the pressure of water in a pipe. The form most commonly found in the market has a dial and movable pointer, the dial being graduated to read pounds per square inch. The principle on which this gage acts is the same as that of the Richard aneroid barometer and the Bourdon steam gage. Within the case is a small coiled tube closed at one end, while the other end is attached to the opening through which the water is admitted. This tube has a tendency to straighten when under pressure, and thus its closed end moves and the motion is communicated to the pointer; when the pressure is relieved, the tube assumes its original position and the pointer returns to zero. There is no theoretical method of determining the motion of the pointer due to a given pressure, and this is done by tests in which known pressures are employed, and accordingly the divisions on the graduated scale are usually unequal. These gages are liable to error after having been in use for some time, especially so at high pressures, and hence should be tested before and after any important series of experiments.

In most hydraulic work the head of water causing the pressure is required to be known. When $p$ is the gage reading in pounds per square inch, the head of water in feet is $h = 2.304p$, or when $p$ is the gage reading in kilograms per square centimeter, the head of water in meters is $h = 10p$. The graduation of the gage dial may be made to read heads directly, so as to avoid the necessity of numerical reduction.

The pressure at any point of a pipe may be measured by the height of a column of water in an open tube, as seen at $A$ in Fig. 36*a*. The upper portion of the tube may be of glass, so that the position of the water level may be noted on a scale held alongside. It is not necessary that the water column should be vertical, and a hose is often used, as seen at $B$, with a glass tube at its top. At $C$ is shown a dial pressure gage. When the head $h$ is directly read in feet, the pressure in pounds per square inch may be computed from $p = 0.434h$. In order to secure precise results when the water in the pipe is in motion, it is necessary that a piezometer tube be inserted into the pipe at right angles; when inclined toward or against the current, the head $h$ is greater or less than that due to the actual pressure at its mouth.

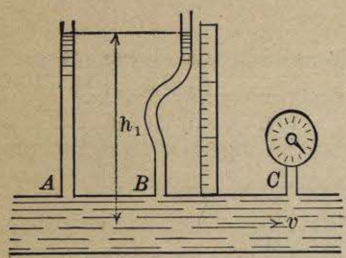

Fig. 36*a*.

For high pressures a water column is impracticable on account of its great height, and hence mercury gages are used. Fig. 36*b* shows the principle of construction, a bent tube $ABC$ with both ends open, having mercury in its lower portion, and the water column of height $h$ being balanced by the mercury column of height $z$. If the atmospheric pressures at $A$ and $C$ are the same, it is evident, from Art. 4, that the height $h$ is about 13.6 times the height $z$, since the specific gravity of mercury is about 13.6. Now $z$ can be read on a scale placed between the legs of the tube, and thus $h$ is known, as also the water pressure at the point $B$. If the atmospheric pressures at $A$ and $C$ are different, as will be the case when $h$ is very large, let $b_1$ be the barometer reading at $A$ and $b_2$ that at $C$, both being in the same linear unit as $h$ and $z$. The absolute pressure at $B$ is that due to the height $sh + s'b_1$, where $s$ and $s'$ are the specific gravities of water and mercury, and the absolute

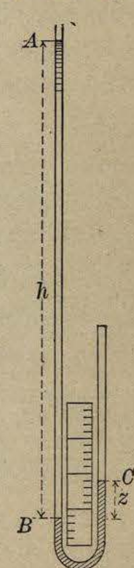

Fig. 36*b*.



pressure at the same elevation in the other leg is that due to the height $s'(z + b_2)$. Since these pressures are equal,

$$h = (s'/s)(z + b_2 - b_1)$$

is the head corresponding to the distance $z$ on the scale. The ratio $s'/s$ is 13.6 approximately, its actual value depending on the purity of the water and mercury and on the temperature.

Fig. 36*c* shows the mercury gage as arranged for measuring the pressure-head at a point $A$ in a water pipe. The top is open to the air and through it the mercury may be poured in, the cock $E$ being closed and $F$ open; the mercury then stands at the same height in each tube. The cock $F$ being closed and $E$ opened, the water enters the left-hand tube, depressing the mercury to

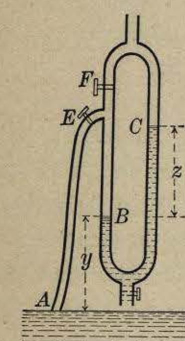

Fig. 36*c*.

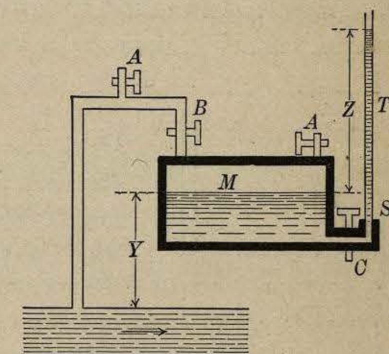

Fig. 36*d*.

$B$, causing it to rise to $C$ on the other side. The distance $z$ is then read on a scale between the two tubes, and the height of $B$ above $A$ by another scale. The pressure of the water at $B$ is that due to the head $13.6z$, and the pressure at $A$ is that due to the head $y + 13.6z$. In precise work it is necessary to determine the exact specific gravity of the mercury and water at different temperatures, so that precise values of the ratio $s'/s$ may be known. The value of $s'$ depends upon the purity of the mercury and is sometimes lower than 13.56.

A better form of mercury gage for use under most conditions is shown in Fig. 36*d*. It consists essentially of a heavy cast-iron reservoir having a large horizontal cross-section as compared with that of the glass tube $T$. The surface of the mercury $M$ in this reservoir therefore remains at a practically constant level, and this level can be seen through a small glass window provided for that purpose. The glass tube is inserted through a stuffing box at $S$ and the flow of mercury into it is controlled by a valve at $C$. Cocks at $A$ permit of drawing off and preventing the entrainment of air, and the water pressure is admitted to the gage through the valve $B$. In case observations are to be made on a pressure which is constantly fluctuating the resulting oscillations in the tube can be dampened by partially closing the valves at either or both $B$ and $C$.

For very high pressures, such as are used in operating heavy forging-presses, the mercury column of the above gage would be so long as to render it impracticable, and accordingly other methods must be employed. Fig. 36*e* represents a mercury gage constructed on the principle of the hydraulic press (Art. 10). $W$ is a small cylinder into which the water is admitted through the small pipe at the top, and $M$ is a large cylinder containing mercury to which a glass tube is attached. Before the water is admitted into $W$ the mercury stands at the level of $B$ in both the glass tube and large cylinder, if the piston does not rest on the mercury. When the water is admitted, its pressure on the upper end of the piston is $pa$, if $p$ is the unit-pressure and $a$ the area of the upper end. If $A$ is the area of the lower end of the piston, the total pressure upon it is also $pa$, and hence the unit-pressure on the mercury surface is $p \cdot a/A$, and this is balanced by the column of height $z$ in the glass tube. For example, suppose that $A = 200a$, then the unit-pressure on the mercury surface is $0.005p$; further, if $z$ be 60 inches, the unit-pressure at $B$ is about $2 \times 14.7 = 29.4$ pounds per square inch (Art. 4), and accordingly the pressure in $W$ is $p = 200 \times 29.4 = 5880$ pounds per square inch, which corresponds to a head of water of about 13 550 feet.

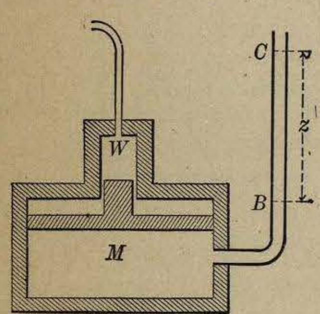

Fig. 36*e*.

Prob. 36. The diameter of the large end of the piston in the last figure is 15 inches, and the diameter of the mercury column is ¼ inch. Find the distance the piston is depressed when the mercury rises 60 inches.



## Art. 37. Differential Pressure Gages

A differential gage is an instrument for measuring differences of heads or pressures, and this must be frequently done in hydraulic work. One of the simplest forms is that seen in Fig. 37*a*, where two water columns from $A$ and $D$ are brought to the sides of a common scale upon which the difference of height $BC$ is directly read. A better form is one having two glass tubes

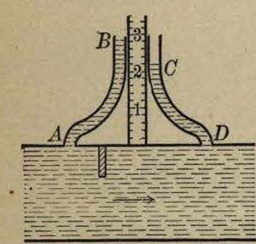

Fig. 37*a*.

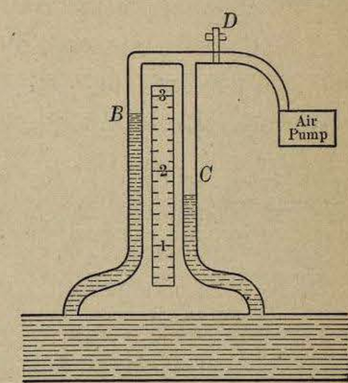

Fig. 37*b*.

fastened to a scale, these tubes being provided with attachments upon which can be screwed the hose leading from the pipe. Where it is desired to measure the difference between two large heads, provided that this difference is not greater than can be read on the scale board, this can be done by connecting the tubes across their tops, as in Fig. 37*b*, and by means of an air pump imposing a pressure sufficient to bring the water columns within visible range. After this pressure has been imposed the valve at $D$ is closed and the difference in the heads read on the scale.

Fig. 37*c* shows the principle of the mercury differential gage.* Two parallel tubes are open at the top, and here the mercury is poured in, the cocks $E$ and $F$ being open and $A$ and $C$ closed; the mercury then stands at the same height in each tube. The cocks $E$ and $F$ being now closed and $A$ and $C$ opened, the water

* For the details of construction see paper by Kuichling in Transactions American Society of Civil Engineers, 1892, vol. 26, p. 439.

enters at $A$ and $C$, and the mercury is depressed in one tube and elevated in the other. Let the pressure at $B$ be that due to the head $h_1$, and the pressure at $C$ be that due to the head $h_2$, and let $h_1$ be greater than $h_2$; also let the distance read on the scale between the two tubes be $z$. Then $h_1 = h_2 + 13.6z$, or the difference of the heads of water on $B$ and $C$ is $h_1 - h_2 = 13.6z$. Thus if $z$ be 1.405 feet, the difference of the heads is 19.1 feet. Here, as for the mercury gage of Art. 36, the specific gravity of the mercury and water must be known for different temperatures, or comparisons of the instrument with a standard gage must be made.

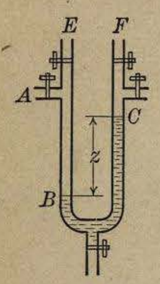

Fig. 37$c$.

When the difference of the heads is small, the water gage, explained in the first paragraph, cannot measure it with precision, especially when the columns are subject to oscillations. To increase the distance between $B$ and $C$ and at the same time decrease the amount of oscillation, the oil differential gage, invented by Flad in 1885, may be used. Fig. 37$d$ shows the principle of construction.* The cocks $A$ and $D$ being closed and $F$ open, sufficient oil is poured in at $F$ to partially fill the two tubes. Then $F$ is closed and the water admitted at $A$ and $D$, when it rises to $B$ in one tube and to $C$ in the other, the oil filling the tubes above the water. Let $s$ be the specific gravity of the water and $s'$ that of the oil, let $h_1$ be the head of water on $B$ and $h_2$ that on $C$, then $sh_2 = sh_1 + s'z$, whence $h_2 - h_1 = (s'/s)z$. Kerosene oil having a specific gravity of about 0.79 is generally used, and if the specific gravity of the water be unity, the difference of the heads is $0.79z$. Thus $z$ is greater than $h_2 - h_1$, and hence an error in reading $z$ produces a smaller error in $h_2 - h_1$. The specific gravities of the oil and water must be determined, however, so that $s'/s$ can be

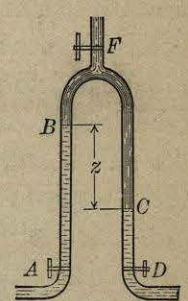

Fig. 37$d$.

*For the details see paper by Williams, Hubbell, and Fenkell in Transactions of American Society of Civil Engineers, 1902, vol. 47, pp. 72–83.



expressed to four significant figures when precise work on low heads is to be done.

The difference of head $h_1 - h_2$, determined by these differential gages, is the difference of the heads due to the pressure at the water levels $B$ and $C$. The difference of the actual heads at the points of connection with the pipe under test is next to be determined. Fig. 37$e$ shows a mercury gage set over a water pipe for the purpose of determining the loss of head due to a

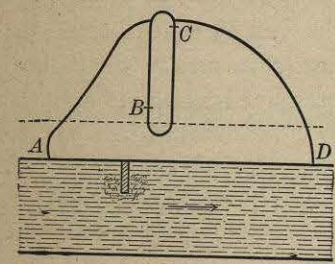

Fig. 37$e$.

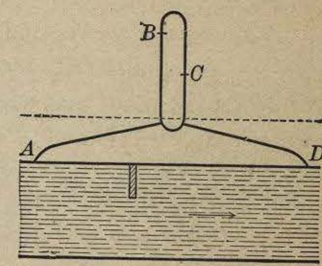

Fig. 37$f$.

valve, the velocity of the water being high, so that the difference of pressure at $A$ and $D$ is large. Fig. 37$f$ shows an oil gage set over a similar pipe, the velocity being low, so that the difference of pressure is small. Let a horizontal plane, represented by the broken line, be drawn through the zero of the scale of the gage, and let $d$ be the distance of this plane above the horizontal pipe. Let $b$ and $c$ be the readings of this scale at the water levels $B$ and $C$ in the gage tubes, the difference of these readings being $z$. Let $h_1$ and $h_2$ be the pressure-heads on $B$ and $C$, and $H_1$ and $H_2$ those on $A$ and $D$. Then $H_1 = h_1 + b + d$ and $H_2 = h_2 + c + d$, and the difference of these heads is

$$H_1 - H_2 = h_1 - h_2 + b - c$$

which is applicable to both kinds of differential gages. For the mercury gage the head $h_1 - h_2$ equals $13.6z$, while the value of $b - c$ is $-z$; hence

$$H_1 - H_2 = 13.6z - z = 12.6z$$

For the oil gage $h_1 - h_2$ is $-0.79z$, while $b - c$ is $z$, hence

$$H_1 - H_2 = -0.79z + z = 0.21z$$