In general, if s' is the ratio of the specific gravity of the mercury or oil to that of the water, the difference of the pressure-heads at A and D, which is the loss of head due to the valve, is $(s' - 1)z$ for the mercury gage and $(1 - s')z$ for the oil gage.

The principle of the mercury gage can also be applied to the measurement of small differences of head by using a liquid having a specific gravity but little heavier than water. Thus Cole, in 1897,* employed a mixture of carbon tetrachloride and gasoline which had a specific gravity of 1.25; for this mixture $H_1 - H_2$ equals $0.25z$, or z is four times the head $H_1 - H_2$, and accordingly when $H_1 - H_2$ is small, the error in determining it by the reading z is greatly diminished. It may be also noted that when the tube or pipe is not horizontal, the expressions $(s' - 1)z$ and $(1 - s')z$ give the loss of head between the two points A and D, although the difference of the actual pressure-heads may be greater or less according as A is lower or higher than D (Art. 85).

Prob. 37. In the case of Fig. 37*d* let the point D be lower than A by 0.45 foot, and let the reading z be 0.127 foot. How much greater is the pressure-head at A than that at D?

Art. 38. Water Meters

Meters used for measuring the quantity of water supplied to a house or factory are of the displacement type; that is, as the water passes through the meter it displaces or moves a piston, a wheel, or a valve, the motion of which is communicated through a train of clock wheels to dials where the quantity that has passed since a certain time is registered. There is no theoretical way of determining whether or not the readings of the dial hands are correct, but each meter must be rated by measuring the discharge, in a tank. Several meters may be placed on the same pipe line in this operation, the same discharge then passing through each of them. When impure water passes through a meter for any length of time, deposits are liable to impair the accuracy of its readings, and hence it should be rerated at intervals.

The piston meter is one in which the motion of the water causes two pistons to move in opposite directions, the water

* Transactions American Society of Civil Engineers, 1902, vol. 47, p. 276.

leaving and entering the cylinder by ports which are opened and closed by slide valves somewhat similar to those used in the steam-engine. The rotary meter has a wheel enclosed in a case so that it is caused to revolve as the water passes through. The screw meter has an encased helical surface that revolves on its axis as the water enters at one end and passes out at the other. The disk meter has a wabbling disk so arranged that its motion is communicated to a pin which moves in a circle. In all these, and in many other forms, it is intended that the motion given to the pointers on the dials shall be proportional to the volume of water passing through the meter. The dials may be arranged to read either cubic feet or gallons, as may be required by the consumers. These meters are of different sizes according to the quantity of water to be registered. They all occasion considerable loss of head in the pipe on which they are installed and are of varying degrees of sensitiveness for small flows. The quantity of water registered by a meter of these types varies on account of wear both with its age and with the quality of the water it measures. For these reasons frequent ratings are desirable.*

The Venturi meter, named after the distinguished hydraulician who first experimented on the principle by which it operates, was invented by Herschel in 1887.† Fig. 38*a* shows a horizontal pipe having an area a_1 at each end, and the central part contracted to the area a_2, with two small piezometer tubes into which the water rises. When there is no flow, the water stands at the same level in these two columns, but when it is in motion, the heights of these columns above the axis of the pipe are h_1 and h_2. Let v_1 and v_2 be the mean velocities in the two cross-sections. Then by Art. 24 the effective head in the upper section is $h_1 + v_1^2/2g$, and that in

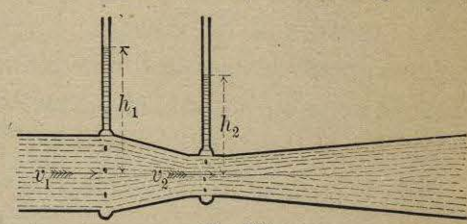

Fig. 38*a*.

* Transactions American Society of Civil Engineers, 1899, vol. 41, and Proceedings American Water Works Association, 1910.

† Transactions American Society of Civil Engineers, 1887, vol. 17, p. 228.

the small section is $h_2 + v_2^2/2g$; if there be no losses caused by friction, these two expressions must be equal, and hence by the theorem of $(31)_2$,

$$v_2^2 - v_1^2 = 2g(h_1 - h_2)$$

Now let Q be the discharge through the pipe, or $Q = a_1v_1$ and also $Q = a_2v_2$. Taking the values of v_1 and v_2 from these expressions, inserting them in the above equation, and solving for Q, gives

$$Q = \frac{a_1a_2}{\sqrt{a_1^2 - a_2^2}}\sqrt{2g(h_1 - h_2)} \qquad (38)$$

which may be called the theoretic discharge. Owing to frictional losses which occur between the two cross-sections, the actual discharge q is always less than Q, or $q = cQ$, in which c is a coefficient whose value generally lies between 0.95 and 0.99. To determine q, when the coefficient is known, it is hence only necessary to measure the difference $h_1 - h_2$, and then compute Q by formula (38).

The Venturi meter is used for measuring the discharge through pipes two inches or more in diameter, the largest meters of this type yet undertaken being those for the new Catskill Water System of the city of New York. Each of these meters will have a capacity of 650 000 000 U. S. gallons per day. They will be constructed of reinforced concrete with bronze throat pieces. The diameter of each end of the meter tube will be 210 inches, while that at the contracted section will be 93 inches.

The contracted section or throat of the meter is usually made from one-quarter to one-ninth of the area of the pipe, and hence the velocity through it is from four to nine times that in the pipe. The throat area used in any particular case is determined from considerations of the various rates of flow to be measured and the resulting throat velocities which should not, in order that the quantity may be well recorded on the automatic recording apparatus, fall much below 3 feet or far exceed 40 feet per second.

In practice the two water columns shown on Fig. 38*a* may be led to a mercury gage, Art. 37, where the difference between the pressure heads h_1 and h_2 is shown by the difference in level of the

two mercury columns. A scale graduated so that $h_1 - h_2$ varies very nearly as q^2 will then enable the rate of flow in the pipe to be directly read (38). This meter is extensively used for the measurement of water and other liquids, and its capacity and accuracy are greater than that of any other form yet devised.

In Fig. 38*b* is shown a type of continuous recording apparatus as constructed by the Builders Iron Foundry of Providence, R. I., for use with the Venturi meter. On the upper dial, which is driven by a clock, a pen makes on a chart a continuous autographic record of the rate of flow through the meter. By means of this chart and a special planimeter the quantity of water which has passed the meter may be determined for any desired period. Depending on the gear of the clock, these charts are changed every 24 hours, every week, or at any other desired interval. On the central dial the mechanism automatically records the total quantity of water which has passed through the meter from the time it was set to the time any reading of

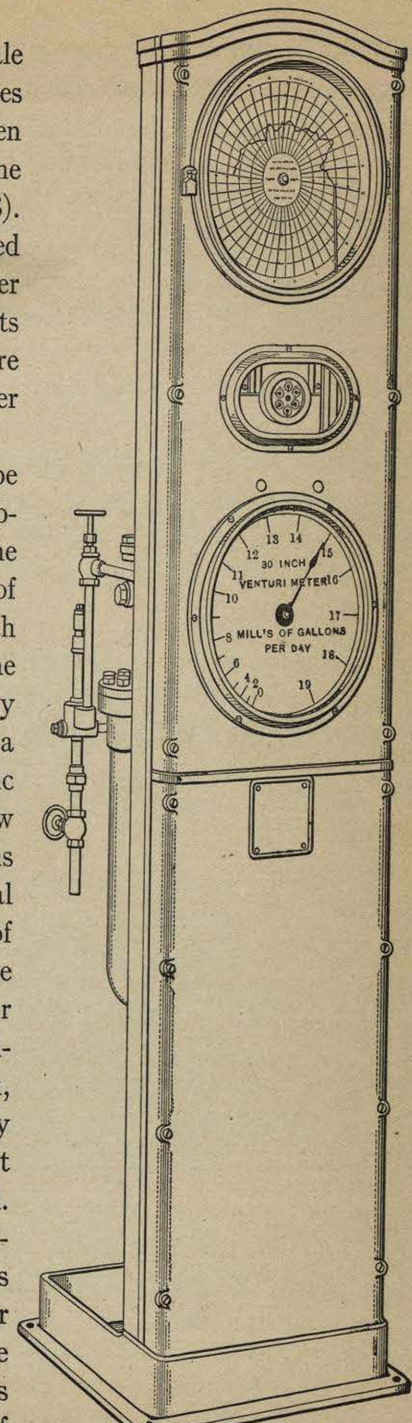

Fig. 38*b*.

the face is taken. On the lower dial the pointer continuously indicates the rate of flow, and, depending on the graduations of the scale, may indicate in millions of gallons per day, in cubic meters per second, or in any other desired unit.

A brief description of the operation of this apparatus is as follows. The two pressure pipes from the meter tube, Fig. 38*a*, are led to two mercury chambers connected near their bottoms and so forming a differential gage. In each of these chambers is a cast-iron float, and each float carries a toothed rack. Each rack meshes with a spur gear, both gears being attached to a single shaft which carries the pointer on the lower dial. The angular movement of this pointer is therefore exactly proportional to any change in the difference of the two mercury levels. Attached to this shaft is a cam, the curve of whose face is proportional to $\sqrt{h_1 - h_2}$. As the shaft rotates the cam presses against and moves a long vertical lever which carries at its top the pen which makes the record on the chart on the upper dial. It is evident therefore (38) that the movement of the pen is proportional to q. The lever which carries the pen is also connected to a clock-driven integrating mechanism in a manner such that the speed of the counter increases directly as the angular movement of the vertical lever increases from its starting position. The speed of the counter is at all times therefore proportional to the rate of flow through the meter, and thus the quantity passing is continuously integrated. The accuracy of this recording mechanism can be tested at any time by comparing the rate of flow indicated by it with the difference between h_1 and h_2 as shown by a differential gage connected to the two pressure tubes leading from the meter. A known difference in pressure may also be imposed upon the pipes leading to the recording mechanism by means of two water columns and the registration of the apparatus observed and compared with this known difference. In this way the apparatus can be tested through greater ranges than those usually to be obtained under service conditions.

Another form of recording apparatus for use with the Venturi meter is made by the Simplex Valve and Meter Company of Philadelphia, Pa.* This apparatus performs all of the functions of that above described. Its operation is also based on a cam but details of its mechanism are materially different.

* Proceedings American Water Works Association, 1906.

The Premier meter * manufactured by The National Meter Company makes use of the Venturi principle though in a manner entirely different from the others above described. It consists essentially of a Venturi tube with a by-pass leading from its upstream end to its throat. On this by-pass, which is materially smaller than the main tube, there is put a displacement meter of the piston type which records that proportion of the entire flow which passes through it. The ratio between the total flow and that indicated by the small meter being determined by experiment, the entire arrangement becomes an instrument for the measurement of water or other liquids. This type of meter is strictly of the proportional type, and as such, is open to all of the objections which hold against the class. It gives best results for throat velocities in excess of 10 feet per second at which the friction in the small recording meter becomes relatively small and consequently has less effect on the strict proportionality of flow through the two branches. This type of meter is adapted to locations close to the hydraulic gradient, where the styles of recording apparatus hereinbefore described could not be used in connection with a simple Venturi tube on account of insufficient submergence of the throat. For the proper operation of these recording mechanisms it is always necessary that the pressure-head at the throat be a positive quantity.

Still another instrument adapted for making a continuous record of the flow of water in a pipe is the Pitotmeter as perfected by Cole.† This apparatus consists essentially of a pair of Pitot tubes, Art. 41, which can be inserted through a corporation cock to any position within the pipe. One of these tubes looks upstream and the other downstream. From them connection is made to the branches of a differential gage in which is placed a mixture of carbon tetrachloride and gasoline (Art. 37). The difference in level between the columns is photographically recorded on a strip of sensitized paper by means of suitable apparatus, and from this

* Proceedings American Water Works Association, 1908; Engineering News, June 16, 1904.

† Journal New England Water Works Association, 1906; Proceedings American Water Works Association, 1907.

recorded difference the quantity of water which has passed through the pipe can be computed. With this apparatus the usual procedure is to first rate the Pitot tubes (Art. 41), and then after inserting them into the pipe, making a traverse in order to determine the ratio between the average and maximum velocities. This ratio usually varies from 0.80 to 0.86 (Art. 83). Thereafter the tubes are set so as to record the maximum velocity, and by means of the ratio the average velocity is computed. In order to insure correct results the tubes must be carefully rated and care be taken to see that they are kept clean of materials deposited from the water about their mouths. The Pitotmeter has the advantage of causing little or no loss of head. It is a very portable instrument, and is particularly adapted for application to water waste investigations, pump slippage, and other allied subjects.

All meters cause a loss in pressure, so that the pressure-head in the pipe beyond the meter is less than in the pipe where it enters the meter. This is due to the energy lost in overcoming friction. For a Venturi tube having a throat area of one-ninth that of the pipe the loss of head in feet is about $0.0021 V^2$, where V is the velocity in the contracted section in feet per second. Thus, when the velocity in a water main is 3 feet per second, the velocity in the contracted section will be 27 feet per second, and the loss of pressure-head due to the meter tube about 1.53 feet.

Prob. 38. A 12-inch pipe delivers 810 gallons per minute through a Venturi meter, a_2 being one-ninth of a_1. Compute the mean velocities in the sections a_1 and a_2. If the pressure-head in a_1 is 21.4 feet, compute the pressure-head in a_2.

Art. 39. Mean Velocity and Discharge

In Chap. 3 the velocity of water flowing from an orifice, or through a tube or pipe, was regarded as uniform over the cross-section. If a is that area, and v the uniform velocity, the discharge is $q = av$; hence, if a and v can be found by measurement, q is known. In fact, however, the velocity varies in different parts of a cross-section, so that the determination of v cannot be directly made. Yet there always is a certain value for

v, which multiplied into a will give the actual discharge q, and this value is called the mean velocity.

In the case of a stream or open channel the velocity is much less along the sides and bottom than near the middle. A rough determination of the mean velocity may be made, however, by observing the greatest surface velocity by a float, and taking eight-tenths of this for the approximate mean velocity. Thus, if the float requires 50 seconds to run 120 feet, the mean velocity is about 1.9 feet per second; then if the cross-section be 820 square feet, the discharge is 1560 cubic feet per second.

The practical object of determining the mean velocity is, in nearly all cases, to determine the discharge, but as a rule the mean velocity cannot be directly observed. A knowledge of its value, however, is necessary in all branches of hydraulics, since hydraulic coefficients and formulas are based upon it. Accordingly, many experiments have been made upon small orifices and pipes by catching the flow in tanks and thus determining q, then the mean velocity has been computed from $v = q/a$. This process has been extended, by indirect methods, to large orifices and pipes, and finally to canals and rivers.

A common method of finding the discharge of a stream is to subdivide the cross-section into parts and determine their areas a_1, a_2, etc., the sum of which is the total area a. Then, if v_1, v_2, etc., are the mean velocities in these areas, and if these are determined by observations, the discharge is

$$q = a_1v_1 + a_2v_2 + a_3v_3 + \text{etc.} \qquad (39)$$

Here the mean velocities may be roughly found by observing the passage of a surface float at the middle of each subdivision and multiplying this surface velocity by 0.9. There are, however, more precise methods, one of which will be explained in Art. 40, while others will be described in Chap. 10. When q has been found in this manner, the mean velocity of the stream may be computed, if desired, by $v = q/a$.

Fig. 39a.

Formula (39) applies also to a cross-section of any kind. Thus, let the pipe of Fig. 39*b* be divided by concentric circles into the areas, a_1, a_2, a_3, a_4, and let the mean velocities v_1, v_2, v_3, v_4, be determined by observation for each of these areas; the discharge q is then given by (39). Again, in the conduit of Fig. 126*a*, let a velocity observation be taken at each of the 97 points marked by a dot, these points being uniformly spaced over the cross-section, so that each of the areas a_1, a_2, etc., may be regarded as $\frac{1}{97}a$. Then from (39) the discharge is

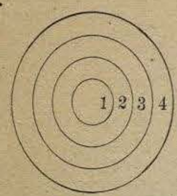

Fig. 39*b*.

$$q = \tfrac{1}{97}a(v_1 + v_2 + v_3 + \cdots + v_{97}) = av$$

or v is the sum of the individual velocities divided by 97. In general, if a cross-section be divided into n equal parts, the mean velocity is the average of the n observed velocities. This result is the more accurate the greater the number of parts into which the cross-section is divided. If the number of parts be infinite and the water passing through each be called a filament, the mean velocity in the cross-section may be defined as the average of the velocities of all the filaments.

Prob. 39. A water pipe, 3 inches in diameter, is divided into three parts by concentric circles whose diameters are 1, 2, and 3 inches. The mean velocities in these parts are found to be 6.6, 4.8, and 3.0 feet per second. Compute the discharge and mean velocity for the pipe.

Art. 40. The Current Meter

In 1790 the German hydraulic engineer Woltmann invented an apparatus for measuring the velocity of flowing water which was later improved by Darcy and others, and is now extensively used for gaging streams and other open channels. This meter is like a windmill, having three or more vanes mounted on a spindle and so arranged that the face of the wheel always stands normal to the direction of the current, the pressure of which causes it to revolve. The number of revolutions of the wheel is approximately proportional to the velocity of the current. In the best forms of this instrument the number of revolutions made

in a given time is determined and recorded by an apparatus placed near the observer on a bridge, in a boat, or elsewhere. In these forms an electric connection is made and broken at every fifth revolution and a dial on the recording apparatus affected. By means of a telephone receiver the making and breaking of the circuit can be made audible to the observer, who in such case simply keeps count of the number of clicks and observes on a stop-watch the time elapsed for a given number of revolutions.

The meter may be operated by placing it on a rod on which its position may be changed at will or by suspending it from a chain or rope. The former of these methods is applicable only to small streams and to cases where the velocity is low. Under the second method the meter can best be operated from a bridge, and in some cases at permanent gaging stations in lieu of a bridge a wire cable may be stretched across the stream and at a sufficient height above it, so that the operator, when seated in a cage which travels on the cable, will have room for operation. On very large streams or where the expense of a cable is not warranted the gagings may be made from a boat. At times of low water, in shallow streams the meter is carried and held di-

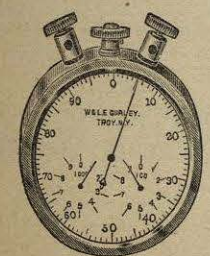
Fig. 40*a*.

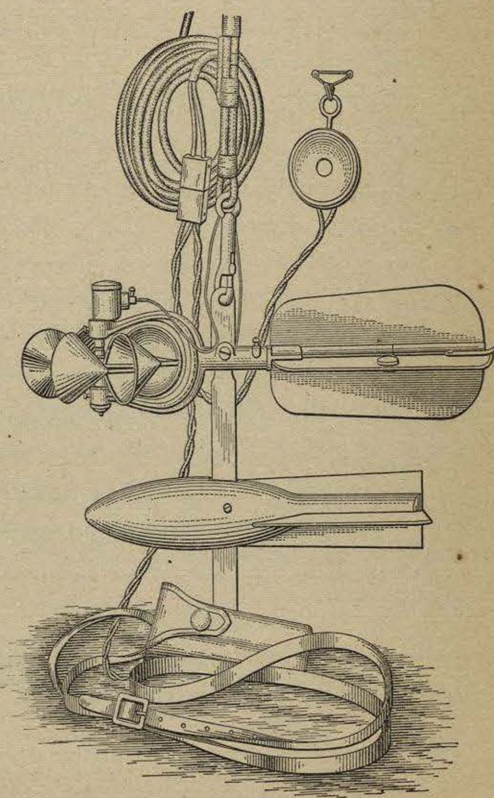
Fig. 40*b*.

rectly in position by the observer who wades out into the stream. In such cases care must be taken to hold the meter clear of the disturbing influence of the observer's presence.

Figure 40*a* shows the recording dial of an electrically operated device for counting the revolutions of a meter, and in Fig. 40*b* is shown the Price current meter, a form extensively used in the United States. The cups or vanes are kept facing the current by means of the cross-shaped rudder immediately behind them. At the lower end of the standard is a heavy torpedo-shaped lead weight also equipped with rudder vanes. The supporting cable is shown connected to the upper end of the standard by a snap, and the electric connection wires are shown extending from the battery in the leather case through the meter and thence to the telephone receiver. Both the battery and the receiver are carried by the observer. In order to assist in keeping the meter more nearly vertical in swiftly flowing streams a line may be attached to the supporting cable a short distance above the meter and carried to some point upstream, so that a pull on it will help to make the meter better maintain its position.

A current meter cannot be used for determining the velocity in a small trough or channel, since the introduction of it into the cross-section would contract the area and cause a change in the velocity of the flowing water. In large conduits, canals, and rivers it is, however, a convenient and accurate instrument. By simply holding it at a fixed position below the surface the velocity at that point is found; by causing it to descend at a uniform rate from surface to bottom the mean velocity in that vertical is obtained; and by passing it at a uniform rate over all parts of the cross-section of a channel the mean velocity v can be directly determined. This latter procedure is one which can be put into practice only in small channels and under unusual conditions. It is mentioned here simply to illustrate the various uses to which the current meter may be put.

In operation the current meter is generally suspended from a cable which is graduated so that the distance of the center of the meter below the surface of the water can be directly read by the observer. The current meter, like every other instrument, must be used and handled with care to produce

the best results. Hoyt * has well summarized recent current meter practice and the results which have been obtained.

To derive the velocity of the water from the number of recorded revolutions per second the meter most first be rated by pushing it at a known velocity through still water. The best place for doing this is in a pond or navigation canal, where the water has no sensible velocity. A track is built along the bank on which a small car can be moved at a known velocity. From this car the meter is suspended into the water either from a rod or a cable, and the method of suspension used should be the same as that to be employed in actual service. The lowest velocity of the car should be that at which the meter will just start and continue revolving; this velocity is from 0.1 to 0.2 feet per second. The highest velocity should be somewhat in excess of the actual velocities to be observed, and ratings are usually carried up to velocities of from 10 to 15 feet per second. It is always found that the number of revolutions per minute is not exactly proportional to the velocity of the car, and hence when the meter is held stationary in running water, the velocity of the water is not proportional to the number of revolutions.

From the observations made at the different known velocities there is prepared a rating table showing the velocity of the water in feet per second corresponding to the number of meter revolutions. This form of table is best, since in making observations best results are obtained by noting the number of seconds required to complete a certain number of revolutions. To make such a table the known velocities of the car are taken as abscissas on cross-section paper and the number of revolutions as ordinates, and a point corresponding to each observation is plotted. A mean curve may then be drawn to agree as closely as possible with the plotted points, and from this curve the velocity corresponding to any number of revolutions can be taken off. This curve may be expressed by an equation of the form $V = a + bn$ or $V = a + bn + cn^2$, in which V is the velocity of the car in feet per second and n in the number of revolutions of the meter per second. By the

* Transactions American Society of Civil Engineers, 1910, vol. 66, p. 70.