DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

CURRENT METERS

FOR USE IN RIVER GAUGING

By

M. A. HOGAN, Ph.D., D.I.C.

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PREPARED FOR THE

COMMITTEE ON GAUGING RIVERS AND TIDAL CURRENTS

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PREFATORY NOTE

The Committee on Gauging Rivers and Tidal Currents was appointed by the Department to prepare a conspectus of information available as to the methods and appliances which have been used in investigations bearing upon measurements of river flow or of tidal and other currents, and as to the arrangements for the testing and standardising of such apparatus, and to test such appliances as appear to be suitable for use in the study of the water power resources of this country.

The following report has been prepared by Dr. M. A. Hogan on the instructions of the Committee, and is intended to bring together in a summarised form the information available as to the conditions affecting the design and use of current meters, and to give a description of those types now in use.

A bibliography of the more recent literature on the subject which is available in the principal London libraries has been prepared. In view of the cost involved, it was not considered worth while printing this bibliography, but type-written copies have been deposited with those libraries likely to be interested. A shorter bibliography of the literature dealing with current meters is included in this publication.

While preparing this report Dr. Hogan visited France and Switzerland. The Department is indebted to the Chief Engineers and other officials of the Service des Forces Hydrauliques (France) and of the Service des Eaux (Switzerland) for the information supplied and for the kindness and courtesy they extended to Dr. Hogan.

Department of Scientific and Industrial Research,
16, Old Queen Street, Westminster,
London, S.W.1.

June 1922.

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I.—INTRODUCTION

1. The Problem of River Gauging

River gauging operations have for their object the determination of the volume of water flowing in the stream past a given section. This quantity is referred to as the discharge of the river. For some purposes extreme conditions of discharge may alone be of interest, but, as a rule, it is the mean flow, its duration and the duration of flows less than this mean which are of importance. To determine the mean flow and its duration a continuous record of the daily discharge of the river is required.

The production of such a record of daily discharges is rendered possible by the fact that a constant relation exists between the depth of water and the discharge in natural river channels. The use of this relation reduces the problem from that of recording discharges to one of recording water levels. The record of water levels or river stages may readily be kept either by an observer reading a fixed scale or by an automatic recorder.

The reason for the simple relation between river stage and discharge may readily be seen. The discharge at any place is equal to the area of the cross-section of the river multiplied by the mean velocity of flow of water across it at the time of observation. The area of the cross-section depends on its shape and on the depth of water and hence on the stage. Further, the mean velocity depends on the surface slope, the rugosity of the channel and on the mean hydraulic radius of the section. That the last is directly dependent on the stage is obvious, and the connection between surface slope and stage is not any more complicated, since the surface slope is but a measure of the difference in stage between two adjacent stations.

It is necessary to remember that the relation between gauge height and discharge just explained only holds for natural river channels. Where natural slope conditions do not obtain, whether due to the pondage caused by dams, tides or to flooding in a tributary, the gauge height is in itself no criterion of the discharge. Even under natural conditions errors will occur due to the anomalous slope relations which prevail when the discharge is undergoing rapid variation. In the case of a rapidly rising river the actual discharge will exceed the normal at any given stage, while on a rapidly falling river the actual discharge will be less than the normal. However, the errors arising from this cause are unimportant in all rivers except those of very irregular régime. On rivers and channels where artificial conditions of flow prevail the discharge may be obtained by simultaneous measurements of the depth and surface slope.[38*]

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* These numbers throughout the report refer to the Bibliography, see p. 31.

2. The Measurement of Discharge

In order to fix the quantitative relation between gauge height and discharge, it is necessary to calibrate the section. This is done by measuring several individual discharges at values well distributed over the range of stage prevailing there, and plotting the results against the corresponding gauge heights to get the stage discharge curve. In the case of rivers flowing in a rock channel the station is calibrated once and for all, but in channels of more unstable material it is necessary to watch for modifications in the section and corresponding alterations in the stage discharge curve. In many rivers which are subject to severe flooding, the channel is changed after each flood, and a stage discharge curve is only valid in the interval between one flood and another.

Three methods are available for the direct measurement of river discharge :—

I. Weir and sluice methods.
II. Chemical methods.
III. Velocity-area methods.

To give anything more than a very brief account of these methods would require much more space than is at present available. In general, weirs and sluices are only available for the measurement of small volumes of water, while velocity-area methods are mainly used for large volumes, but this division is not by any means rigid. Chemical methods are theoretically applicable to all volumes of flow, but in practice, on account of their cost, they are becoming restricted to the measurement of small volumes.

3. Weir and Sluice Methods of Discharge Measurement

Weirs of suitable form are undoubtedly the most accurate means available for the continuous measurement of large volumes of water. However, the expense of construction renders the use of the weir for measuring purposes alone, impossible except on small streams. In some cases it may be possible to use for measurement a weir which is required for some other purpose. The usual drawback to the use of a weir built and used for power or navigation lies in the fact that all the water does not pass over the weir but some goes through sluices and locks or turbines. The usefulness of the site as a discharge station will depend on the accuracy with which the amount of water so passed through may be measured.

In the case of the normal weir we require to have a record of the head of water over the sill and to know the coefficient of the weir. The former may readily be obtained by installing an automatic water-level recorder in a suitable position upstream of the weir. Should there be any possibility of the tail water rising to such a level as to drown the weir, a record of its height should also be kept. The coefficient, or law connecting height and discharge for the weir, may be determined either by direct experiments on the weir itself or by experiments on suitable models. In the case of many of the standard types of weir the coefficients have been determined by the U.S. Geological Survey,[21] and these may be used if the conditions allow. In the case of weirs of irregular profile the only satisfactory course is to measure the coefficients. It may be possible to do this by measurements with a current meter or even by direct volumetric measurement at specially favourable sites. Usually, however, it will be simpler to work out the coefficients by experiments on a sufficiently large-scale model.

All the remarks made as to the determination of the coefficients for overflow weirs apply with even greater force to sluices. In the case of the sluice there is another variable present, the degree of opening. The coefficients may be determined experimentally in a similar manner to those of a weir. Reference may be made to the very interesting series of experiments carried out on the Nile Dam at Aswân, as a result of which it is now possible to measure the low water flow of the river with great accuracy.[29] The water passed through turbines does not present so much difficulty, since the discharge at various loads is always tested before acceptance of the machine. It is only a question of keeping a record of the turbine gate openings. Nevertheless, the fact that the efficiency of the runner diminishes with age must be kept in view.

4. Chemical Methods

Chemical methods of gauging the flow of liquids have been known for a very long time, but the application to stream gauging is comparatively recent. The method is very simple and attractive in theory, but the experimental precautions required to ensure a sufficient degree of accuracy are very troublesome.[14, 15] Essentially the method consists in the feeding of a solution of some suitable chemical of known concentration into the river at a known and constant rate for a period of ten or twenty minutes. A certain distance downstream samples of the river water are taken extending over this period, and by titrating for the salt the dilution of the dosing solution is found and thence the volume flowing in the river. The experimental precautions referred to concern the mixing of the solution with the river, the representative character of the samples titrated, and the composition of the river water itself. Recently this method has been abandoned by the Swiss Hydrometric Service on the ground of excessive expense.

Before passing, mention may be made of another type of gauging also depending on mixtures: temperature gauging.[36] This method of gauging was developed in the French Alps, where the temperatures of adjacent streams vary very considerably, depending on whether they are or are not directly of glacial origin. All that is required are temperature measurements of the two streams before junction and of the combination after mixture. From this the ratio of the volumes of water in the two streams is arrived at, and if one volume be known the other may be derived.

5. Velocity Area Methods

Velocity area methods of discharge measurement depend on the determination of the two factors, mean velocity and area of cross-section, which go to make up the discharge. The measurement of the area of the cross-section does not, as a rule, present any serious difficulties, since it only involves the taking of soundings at fixed points across the stream. The taking of soundings becomes difficult when the water is very deep or the velocity high, and a heavy weight suspended by piano wire must be used.[8] However, the determination of the mean velocity is a more difficult operation.

The mean velocity may be obtained either indirectly, from measurement of the surface slope and the application of a formula such as that of Ganguillet and Kutter, or, directly, by measurement with floats or current meter. There are many objections to the use of the slope method. The slope itself is a difficult quantity to measure with sufficient accuracy. A large number of cross-sections must be taken. Finally, the choice of the proper coefficient of rugosity is a matter of very considerable difficulty. Nevertheless, in the hands of skilful workers the method is capable of yielding very good results. The case to which this method is specially applicable is the measurement of flood discharges after the flood has cleared away. In the studies of the Engineering Commission on the Ohio floods of 1913 the slope method was used and checked against other methods.[19] Their conclusions go to show that the Kutter formula is the best available for the calculation of velocity, but that it needs modification. As a rule, the discharges calculated from slopes in different parts of the same channel agreed to within 10 per cent.

Velocity may be measured either directly by means of floats or indirectly by current meter. The velocity observations have for their object the determination of the mean velocity, but since the velocity is not uniformly distributed over the section it is necessary to take account of its variations. Taking vertical cross-sections parallel to the axis of the channel, the curve of distribution of velocity, or vertical velocity curve, is approximately a parabola with axis horizontal and vertex in, or close to the surface. In horizontal sections the maximum velocity occurs at the centre of the channel and the velocity diminishes on approaching the banks. These variations exercise an important influence on the methods used to obtain the mean velocity.

6. Float Methods

Floats are used to give a direct measurement of the velocity of the water. There are three types, surface floats, rod floats, and twin floats. In use a portion of the river with as uniform as possible a section is chosen. and cross-sections must be measured at many points along the reach used for timing the floats. The operations of starting and timing the floats do not call for any special comment, save that, on most rivers, two boats will be required, one for starting and the other for stopping the floats, together with two instrument men on shore. Thus, the use of floats as a rule demands a large party. It must be remembered that a float only partakes of the velocity of the assemblage of water particles with which it is in immediate contact, and that hence it is necessary to run several floats over the same course in order to obtain a mean velocity.[7] The number of repetitions required will depend on the accuracy desired, but five runs is usually sufficient.

Rod floats would seem most likely to give good results, and this is the case within the limitations of their use. They are made either of wood or metal tubing so weighted that, when placed in water the rod remains vertical with not more than a few inches of its length appearing above the surface. Bearing in mind the parabolic shape of the vertical velocity curve, and the fact that the force acting on the float at any point is proportional to the square of the difference between the velocity of the rod and of the water in contact with the rod, it is easy to show that the ratio of the velocity of the rod to the mean velocity of the water is dependent on the ratio of the length of the rod to the depth of the water. Francis gives the formula

$$V_m = V_r \times (1{\cdot}012 - {\cdot}116 \frac{h-l}{h})$$

where V_m is the mean velocity, V_r is the velocity of the rod, l its length and h the depth of the stream. In practical work the principal errors peculiar to rod floats arise from the fact that the irregularities in natural stream beds are usually so great that a rod of sufficient length cannot be used, and that the ratio of the length of the rod to the depth of the stream is continually varying. In artificial channels rod floats give results of a very high degree of precision.[34]

Double floats were at one time very popular. They essentially consist of a heavy body which sinks in the water, but is upheld at a certain depth by a wire connecting it to the float which remains at the surface. The idea underlying this arrangement was that the distance between the two bodies should be so adjusted that the combination would move with a velocity equal to the mean velocity in the vertical. Unfortunately the two bodies do not keep at the correct distance apart, the lower one gets left behind and tends to rise, thus producing exaggeration of the record.

Surface floats have also been used very frequently. The surface float measures the velocity of the surface layer of water. However, the surface velocity does not bear a fixed relation to the mean velocity. It depends on the depth of the stream and on the mean velocity. The coefficient required to reduce the surface to the mean velocity varies from ·98 and ·78, but ·85 is a good average value.[34] The surface velocity is greatly influenced by the action of wind on the water surface, and hence observations by means of surface floats become altogether unreliable in windy weather. On the whole, surface floats are only a very indifferent means for the measurement of discharge, and their use should be restricted to cases of preliminary work where resources for more accurate observations are not available, or in the case of floods when the presence of floating drift makes the use of the current meter impossible.

7. The Current Meter

The current meter is an instrument which, when held in a moving stream of water, gives an indication of the velocity of flow. It should be noted that whereas the float moves with the water and hence indicates its velocity directly, the meter remains fixed and is operated either by the pressure or velocity of the moving water. Two types of meters may be distinguished : those worked by the impact pressure of the water and those which depend directly on the velocity. The Pitot tube and the various types of plate meter belong to the first class, while the second class are all meters with a rotating element. These latter are the usual type at the present time.

The Pitot tube is not in favour for river work.[13,30] This is partly due to its lack of sensitiveness to low velocities. The instrument measures the "velocity head" $\frac{v^2}{2g}$, of the water, this being the difference in the pressures on two orifices, one of which faces upstream and the other of which is at right angles. This pressure difference is measured by means of a U-tube manometer. At a velocity of, say, 2′ per second, the velocity head is equal to ·75 of an inch of water, and if a water-air manometer be used this is the actual value read on the scale. However, it is possible to multiply this reading up to about four times when a differential liquid manometer using water and a mixture of carbontetrachloride and benzene with a specific gravity of about 1·25 is employed. This would give a 3″ scale reading for a velocity of 2′ per second.

Pressure meters, in which the velocity is inferred from the pressure on a plate exposed to the current, have frequently been used in the past. However, they give unreliable results. Any plate exposed to water flowing faster than a few inches per second gives rise to vigorous vortex production at its rear face. Such vortex formation is essentially a discontinuous phenomenon, and the effect on the plate is that the force on it undergoes frequent violent alterations. In all of the meters so far devised the plate has been supported in a flexible manner in order to allow of the measurement of the pressure either by means of a weight and lever, a spring balance, or a torsion balance. With such a method of support, when the pressure varies continually, it is clear that the plate will be set into vibration and that as a result the pressures recorded will bear out little relation to the actual pressures. Further, it cannot be said that we have any very accurate knowledge of the laws of pressure on flat plates exposed to a water current. The experiments of Dubuat show that the pressure on a plate when held in a stream of water is 50 per cent. greater than on the same plate when towed at the same velocity through still water.[9] Hence it is clear that a plate meter could not be rated in the ordinary way by towing through still water.

At present only meters of the rotating type are used. In these instruments the flowing water turns a wheel or screw. The velocity of rotation of the meter is measured and from it is deduced the velocity of flow of the water. This deduction is made by the aid of an experimental "Rating Curve," which gives the relation between the velocity of rotation of the meter and the velocity of flow. Many points which arise in connection with the use and rating of current meters are discussed later. However, in the following remarks on the use of meters it is assumed that the meter is capable of measuring the mean velocity of flow at a point if allowed to remain there for a long enough interval of time.

8. The Relation between the Various Velocities and the Mean Velocity

The methods of discharge measurement with the current meter have been devised to take into consideration the actual conditions of flow in the river channel. On any vertical the forward velocity is a maximum close to, or at, the surface and falls off towards the bottom, while, in horizontal planes the velocity is a maximum at the deepest portion and falls off towards the banks. To take account of this two dimensional variation in velocity the cross section of the river is divided up into a number of vertical strips and in each of these the mean velocity is found by making velocity observations on one vertical. In this way the discharge of each strip of the cross section is determined and thence the total discharge. The discharge may also be computed by drawing the cross section and plotting on it curves of equal velocity, and measuring their areas, from these, the total volume discharged may readily be determined by the application of Simpson's rule. This method is seldom used in practice both because it requires a large number of observations, and also because the plotting of the contours of equal velocity introduces the possibility of an appreciable personal error.

Several methods of obtaining the mean velocity on a vertical from observations with the current meter are or have been in use. These fall under the headings of vertical velocity curve methods, point or coefficient methods and integration methods.

In the vertical velocity curve method measurements of horizontal velocity are made close to the surface and at equal intervals in depth, making five to ten observations for the vertical. These velocities are plotted with depths as ordinates and velocity as abscissæ, and their mean determined by taking the area of the curve and dividing by the depth (Fig. 1). The vertical velocity curve method is the most accurate available, provided the conditions are suitable. The principal drawback to the use of this method lies in the length of time required to carry out the observations. This may lead to serious error if the discharge and stage are undergoing rapid change. Nevertheless, vertical velocity curves are of great value for determining the coefficients to be used with the other more rapid though less precise methods, and for this purpose it will be profitable to measure a few vertical velocity curves even at stations where the whole section cannot be covered in this way.

The conditions which obtain in practical discharge measurement, more especially on larger rivers, frequently prohibit the use of the vertical velocity curve method, and more rapid means requiring a fewer number of observations have to be employed. For this the point methods have been developed. These are based on the fact that all vertical velocity curves tend towards a similar parabolic shape. If all were identically similar, one observation on a vertical would suffice to give the mean velocity when multiplied by a coefficient depending on the depth of the observation. The most usual depths for single point observations have been at six-tenths, at half depth and at the surface. The difficulties attendant on a choice of the best value of the coefficient to adopt have already been discussed in connection with the use of surface floats and the same difficulties apply to coefficients for other depths. The parabolic shape of the vertical velocity curve implies that the mean velocity must lie at six tenths of the depth while the mean of two velocities at two tenths and eight tenths of the depth must lie very close to the mean velocity. The use of two observations at ·2 and ·8 of the depth gives a greater accuracy than could be expected with only one observation, and this again may be improved by taking three points, ·2, ·6 and ·8, which also give the mean velocity without the use of a coefficient.

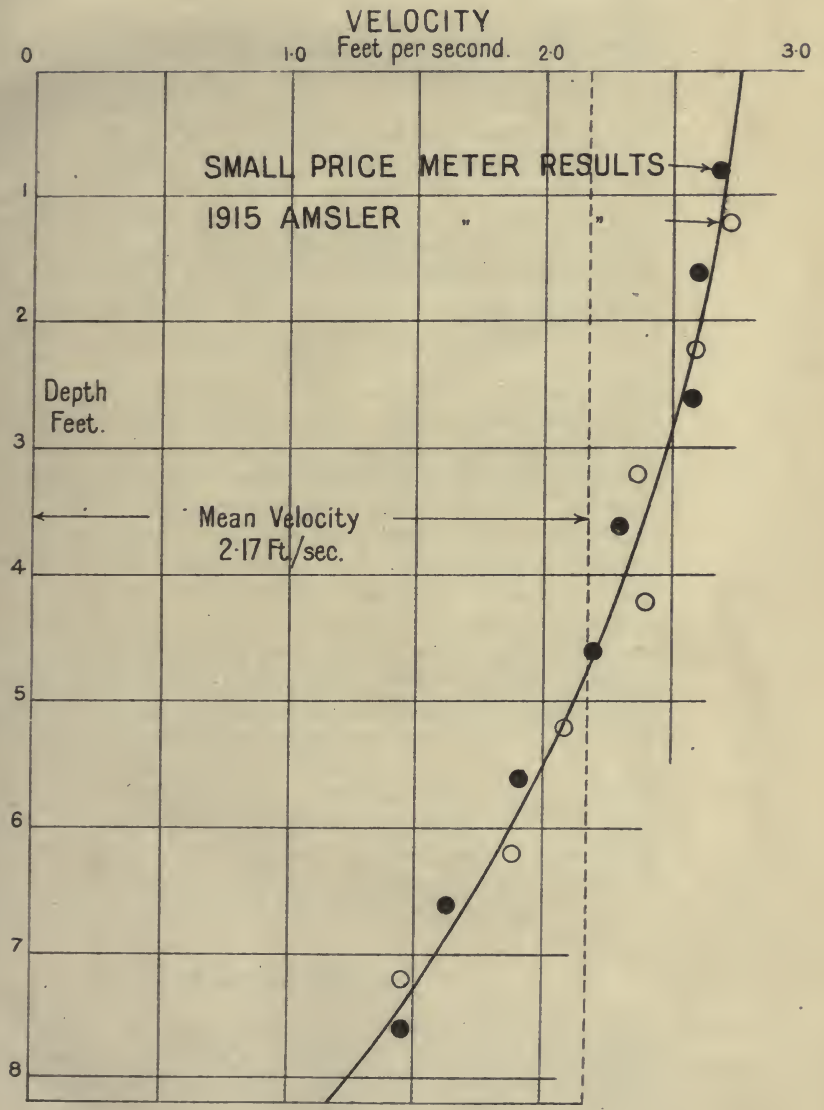
The integration method consists in causing the meter to traverse the depth with a uniform vertical velocity and thus to effect a mechanical integration of the various velocities.[16, 17] This method involves two timing operations, one for the traversing and one for the rotations of the meter, as usual. Hence, in general, a second observer would be required. Some meters, such as the Price, cannot be used for integration, and the method has practically become obsolete.

At the present time the River Gauging Services in France and Switzerland make use of the vertical velocity curve method in all except the most exceptional cases.[10, 44] These occur in flood-time, when the water in the streams is so charged with debris as to render the use of the meter impossible. The United States Geological Survey, on the other hand, rely on point methods, the ·2 and ·8 depth method being most popular. The Egyptian Public Works Department formerly used single observations at half depth, but have recently adopted the vertical velocity curve method in their gaugings on the Nile.

FIG. I.

TYPICAL VERTICAL VELOCITY CURVE.

MEASURED ON THE SEVERN.



II.—REVIEW OF THE CONDITIONS AFFECTING THE USE OF CURRENT METERS

9. General Considerations affecting Rating

Since meters with a rotating element are at present the only type in general use, it is proposed to discuss the conditions of flow in rivers and channels only in relation to the use of such meters. As already mentioned the velocity of the water is deduced from the record of the number of revolutions per second of the meter, by the use of an experimental rating curve. This rating curve is usually obtained by towing the meter through still water at various velocities and plotting the rate of rotation of the meter against the known velocity of towing.

In applying the rating curve thus obtained to reduce the results of observations in moving water it is tacitly assumed that the conditions under which the meter works in both cases are the same. This is by no means a valid assumption. The water is in different states in the two cases. The still water through which the meter is towed may be termed a static fluid, in which the flow approximates to stream line while the moving water is in turbulent motion, and hence, may properly be described as a dynamic fluid.[46]

The experiments of Dubuat, one of which has already been quoted, showed that the pressure on a plane when held in a stream of moving water was up to 50 per cent. greater than the pressure on the same surface when towed through still water at the same velocity. This phenomenon was known as " Dubuat's Paradox " and remained a problem for many years. However, the recognition of two fluid states, static and dynamic, renders an explanation possible. In the static fluid the flow is of a steady type, the plate drags along with it some water, this goes to form a prow and stern, and hence we tow what is really a stream-lined volume of water of which the plate is the centre. In the dynamic fluid the motion is too irregular for any such action to take place and so the plate is subjected to impact pressure on its up-stream and to suction on its down-stream face.

In the case of the rotating type current meters it is possible that the effect may not be so large since they consist not of plates at rest, but of surfaces in motion. Nevertheless, it cannot be assumed to be non-existent, and hence it is necessary to examine the effect of turbulent motion on the records of meters.

10. Turbulent Motion

In what follows, the term turbulent is used to specify any condition of liquid flow in which viscosity is not the controlling factor.[2] In natural channels the velocity is above the critical in all save the most exceptional cases. Normally the amount of energy degraded by a flowing river is of the order of five times that required to overcome the viscous resistances, the surplus going to maintain vortex motion throughout the body of the liquid. It may be noted that this use of the term turbulent conflicts with the popular usage, since in the hydrodynamic sense the flow in practically all rivers is turbulent, while ordinary usage restricts the terms to cases where very violent degradation of energy is taking place.

In order to get some data for the comparison of current meters it is necessary to find out the essential points of difference between turbulent and stream line flow. Two points stand out in which the conditions affecting a meter in turbulent flow differ from those in stream line flow :—

I. The velocity at any point is not constant in magnitude but undergoes continuous variation.

II. The velocity at a point is not constant in direction but moves about making various angles with the axial direction of flow.

It is hardly necessary to point out that a natural consequence of this continuous variability in magnitude and direction of the velocity at a point is that the magnitude and directions of velocities at adjacent points will in general be different.

The cause of this variability in magnitude and direction of the velocity at any point in a flowing stream may readily be understood from a consideration of the nature of turbulent flow. Since the water moves forward in a series of swirls or vortex systems the motion of any water particle will be made up of a rotation about the vortex axis and a forward translation. Thus the absolute velocity of the particle is the resultant of the forward velocity and the velocity of rotation, and hence the more violent the vortex motion the more irregular will be the resultant velocity in magnitude and direction. This description of the velocity of a water particle is directly applicable to the velocity at a point fixed in the stream, since the velocity at the fixed point is but that of the particle which happens to be there at the instant of observation, and the progression of the vortices will bring to it, in sequence, particles of all possible velocities.

Experimental investigations of turbulence in rivers give some idea of the magnitude of these velocity variations. In 1877 on the Elbe, Harlacher obtained a graphical record of the velocity, second by second, at various points on a vertical.[17] Close to the bed of the stream the variations were most acute, velocities of from 60 to 180 per cent. of the mean being observed during the course of one minute. Close to the surface the variations were of smaller amplitude. These variations in magnitude of the velocity are not progressive. When observations are continued over a sufficiently long period the irregularities average out, *e.g.*, Professor Unwin on the Thames found that, while the times for 100 revolutions of the meter were very irregular, the times for 500 revolutions were practically constant.[45] Further and more detailed work on the Danube and Elbe gave results of a similar nature.[24]

On the obliquity in direction of velocity which may occur in rivers we have little information. Experiments by Leliavsky on the Dnieper near Kieff show that obliquities of 20° to 30° were not uncommon both in horizontal and vertical planes.[26, 27]

In discussing the effects of turbulence note must be made of the recent attempt to measure turbulence made by the Physical Department of the Public Works Ministry in Egypt.[47] The difference between ordinary and stream line flow is defined under three different heads (*a*) velocity variations, (*b*) variations in direction of velocity, (*c*) variations in magnitude and direction of the velocity of adjacent particles. The term turbulent is restricted to flow characterised by the last mentioned description.

In order to establish the existence of this type of flow a Ratchet Turbulence Gauge was devised. This is similar to a screw current meter only that the screw is replaced by a paddle or vane both of whose blades lie in a plane containing the axis. Thus the general forward movement of the water will evidently be unable to produce any rotation whatever. If, however, any differential movement exists in the water the action on one blade will, in general, be different from that on the other and some rotation will be produced. As this rotation is as likely to be clockwise as anti-clockwise a ratchet is fitted to prevent one of these taking place. The result is that differential movements in the water produce cumulative rotation of the paddle.

This gauge was used in connection with a Price meter in discharge measurements on the Nile at Aswân and on canals of the Delta Barrage. In use it was found that the ratchet gauge rotated when the water was so turbulent as to cause the Price meter (medium size) to register 15 per cent. excess for the whole discharge. When the station was more suitable for gauging, the ratchet gauge did not rotate. Unfortunately the experiments do not give an idea of the lowest amount of turbulence, as measured by the error in the discharge by the Price meter, which the ratchet gauge is capable of indicating.

Having now outlined the principal points of difference between turbulent and stream line flow it is necessary to examine how these differences affect the record of a current meter.

11. The Effect of Varying Velocity

The existence of variations in magnitude of the velocity renders it necessary for the accurate measurements of the velocity at any point : (i) that the meter should be able to arrive at an arithmetical average of the varying velocity and (ii) that the time of observation should be sufficiently long for the average so obtained to be a representative one.

It would appear that this first requirement is theoretically impossible of attainment with any of the rotating meters. In the case of a Robinson, rotating cup type, anemometer, Stokes has shown that if its rotor be exposed to a velocity varying harmonically between $V+W$ and $V-W$ the indication given by the meter will exceed the true mean velocity by an amount lying between $\frac{W^2}{4V}$ and $\frac{3W^2}{4V}$, inclining to the latter value as the moment of inertia of the rotor is increased.[43] This analysis is only applicable to the case in which the time of oscillation of velocity is the same as the time of revolution of the meter. However, it appears that in rivers the oscillations in magnitude of velocity are likely to be of much longer period. Experiments on meters, which will be referred to later, have shown that when the time of oscillation and of revolution are of the same magnitude the readings of the meter are increased by oscillation, but that when the time of revolution becomes much shorter than the time of oscillation the readings of the meter tend to be slightly lower than their true value. This may readily be explained if the low velocity characteristics of the meters be considered. When a meter oscillates during its transit through still water it is obvious that it will have passed through the same length of water at the end of one period as it would have had there been no oscillation. If the meter recorded correctly at all speeds the indication given should be the same, whether it made the transit with or without oscillation, since the distance moved relative to the water was the same in both cases. However, as will be seen later, the ordinary meter makes a lower number of revolutions per unit length of water passed at low than at high speeds. During one half of an oscillation the velocity of the meter will be less than the normal velocity of transit and may well fall so low that the number of revolutions per unit length of water passed will be less than their high speed value, so that the record of the meter is diminished by oscillation.

The proper time to allow for an observation is a matter which admits of discussion. In making a discharge measurement only a limited amount of time is available, and hence it has to be decided whether observations of long duration giving an approximately correct value of the mean velocity will be made at a relatively small number of points or whether shorter observations should be made at a larger number of points. For use in regular channels the first method would probably be adopted, but in the case of an ordinary discharge station on a natural channel the larger number of points would probably give the better result, on account of the irregularity of distribution of velocity.

12. The Effect of Oblique Velocity

Error may be produced in a discharge measurement made by a current meter as a result of oblique velocity in two ways :

(i) The meter may take up a direction inclined to the normal to the section and measure the full value of the oblique velocity. This will, of course, produce exaggeration of the discharge, since the method of computation assumes that the velocity is measured at right angles to the cross section; and hence only the normal component of oblique velocities should be measured. All meters which are used suspended from a cable such as the Price and Haskell are affected with this error. If the current be inclined to the normal either horizontally or vertically the meter is guided by its tail to measure the full value of the oblique velocity which may be materially in excess of the normal component. If it were feasible to use a direction recording gear it would be possible to calculate the normal components and the swinging meter would give excellent results.

(ii) On the other hand, if the meter be fixed as to its direction it may fail to record the true components of oblique velocities. It is obvious that the only type of rotating meter which can reduce all inclined velocities to their normal components will be one in which the axis of rotation coincides with the normal direction of flow. Such a meter has identical vertical and horizontal characteristics. The question then reduces itself to one of designing the reacting surfaces, or blades, so that the effect of flow inclined to the axis of the meter is decomposed into two parts; that due to flow parallel to the axis which alone should produce rotation, and the other at right angles to the axis which should have little if any effect.

13. Summary of Requirements

The variations in magnitude and direction of velocity which take place at all points in a river render the following properties essential in a current meter in order that it should give an accurate record :—

(i) A low moment of inertia, to minimise error due to velocity variations.

(ii) A mounting, or means of support, which will keep the meter fixed in direction.

(iii) A rotor, so designed as to reduce oblique velocities to their normal components.

In addition to these theoretical desiderata there are others of a practical nature which are just as necessary or perhaps more necessary for the accuracy of the work :

(i) The meter should not offer unnecessary obstruction to the flow of the water, and nothing which could give rise to eddies should project in front of the rotating element.

(ii) The bearings should be well protected from grit and corrosion and so designed as to suffer as little change of form by wear as possible.

(iii) The apparatus as a whole should be sufficiently strong to withstand rough treatment.

There is one further consideration : the range of accurate operation of the meter should cover all velocities likely to be met with in practice. This implies that the meter must be able to measure with accuracy very low velocities.

III.—VARIOUS TYPES OF CURRENT METER

14. Classification of Current Meters

The current meters in use at the present time may be divided into two classes : those in which the axis of rotation is vertical, and those in which it is horizontal. Of the first class there is only one example : the Price meter. All the others, such as the Amsler, Haskell and Ott possess a horizontal axis of rotation. These meters, with one exception, all give indications by way of an electric contact system. That is to say, the rotating portion of the meter operates a contact device after every fifth or other suitable number of revolutions, and this contact operates either a telephone or a bell, and thus allows the revolutions of the meter to be timed.

15. The Price Meter

The only meters with a vertical axis of rotation at present in use are made by W. and L. E. Gurley, of Troy, N.Y., under the patents of W. G. Price, who devised the original model in 1885. Since then, although numerous improvements in detail have been made, the general design remains unaltered.[20, 21]

(a) *Description.*—At present only one size of Price meter is made, but it is obtainable in two patterns, the acoustic and the electric. Both these meters consist of a C-shaped frame carrying the rotating element, which is a wheel made up of six conical buckets or cups. This wheel revolves in a horizontal plane. Its axis is carried on a hard steel pivot at the lower extremity of the frame and passes through a bronze bearing at the upper extremity, beyond which it carries a cam by means of which contact is made.

The acoustic meter is so called because the revolutions of the wheel are made known by the sound of a hammer striking a diaphragm, one signal to each ten revolutions. When in use, the meter is held by a sleeve-jointed wading rod which screws into the frame and, in connection with a rubber tube and ear piece, forms a passage through which the sound of the hammer stroke is transmitted to the ear of the observer. The use of this meter is restricted to work in streams where it is possible for the observer to approach the stream closely.

The electric meter is provided with a contact device and the revolutions of the wheel are indicated by a telephone receiver. The contact chamber is fitted on the upper end of the meter axis. Two patterns are made, one indicating each single revolution of the wheel, while the other indicates each fifth revolution. In use, the meters may either be supported on a rod, or suspended by a cable, the latter being the more usual method. In suspension, the meter is held by a cable attached to a steel weight-hanger which, after passing through the frame, supports the torpedo-shaped weight required to hold the meter in a vertical plane against the current. A tail, consisting of a stem to which are fastened two vanes, is attached to the frame opposite the bucket wheel, and serves the double purpose of balancing the bucket wheel and keeping the meter parallel to the direction of the current. For use with a rod, a socket is provided on the meter frame into which the rod may be screwed, or the rod may be inserted through a special hanger placed between the frame and tail of the meter, thus allowing it to be placed at any point along the rod, whereas in the other arrangement it is fixed at the end.

In the past, other models of the Price meter have been made by Gurley—the large and medium sizes. The medium sized meter has been very extensively used up to quite recently. It differs from the small type meter both in size and in the shape of the cups. However, the small type proved more satisfactory both in accuracy and in ease of manipulation so that the manufacture of the medium type has been discontinued.

(b) *Uses.*—The small Price meter is the standard instrument of the United States Geological Survey and embodies in its design the accumulated experience of over thirty years' stream gauging work by the Survey. It has been developed for use in channels of almost any depth or velocity which may occur among the fifteen hundred gauging stations maintained by the Survey. They are satisfied that under ordinary conditions with a reasonably good gauging station the accuracy of individual discharges measured by the small Price meter is within 5 per cent. This is within the limits of accuracy imposed by the other factors involved in the calculation of the discharge of a stream over any extended period.[15]

The adoption of the Price meter by the United States Geological Survey, which is by far the largest stream gauging organisation in existence, has naturally led to its introduction into most other English speaking countries. For example, in the river gauging work carried out in Canada by the Dominion Water Power Branch and Irrigation Office the small Price meter is used and the methods adopted are similar to those employed in the United States.[40]

In Egypt the Price meter has been used for the measurement of the discharge of the Nile since 1902.

The small Price meter has been used in England by Mr. G. B. Kershaw to measure the low water flow of a number of rivers in connection with the work of the Royal Commission on Sewage Disposal.[23, 37]

(c) *Examination of Criteria.*—Going back to the criteria already stated (*see* p. 13), for the design of a current meter to give accurate records in turbulent water, we find that the Price meter infringes all of them in its normal mode of use :

(i) The moment of inertia of the rotor is large, owing to the concentration of material towards the rim.

(ii) When fixed on a cable the meter is provided with a tail so that it shall face the current and thus the occasion for the third requirement does not arise.

Hence we should expect that the Price meter would give exaggerated results due both to its high moment of inertia and to its measuring velocities which are oblique to the cross section of measurement. On the other hand, if the meter be used fixed to a rod, excess is still to be anticipated in the records, for instead of reducing oblique velocities to their normal components, the wheel will record practically 100 per cent. for any horizontal direction of flow.

(d) *Tests.*—It is now proposed to give a short account of some of the tests which have been made on Price meters.

(i) *Variable Velocity.*—The effect of variable velocity on the rating of small Price meters has been tested in Egypt.[22] The meters were rated by towing from a raft through a still water tank. It was found that the number of revolutions which the meter made during a run of 50 metres was very nearly the same whether the towing was regular or very irregular. The error rose from zero at a velocity of 1 metre per second to 4 per cent. at a velocity of 0·3 metres per second which was the lowest velocity used in the trial.

On the other hand tests carried out by Groat in the Naval Tank of the University of Michigan give positive results.[14] In this case the meter was made to oscillate in a longitudinal direction relative to the car while the latter moved forward at a uniform velocity. The results show that when the velocity of oscillation was almost equal to that of progression the records of the meter were very much in excess of their true value. At higher velocities of progression the general effect of oscillation seems to have been to cause a reduction in the readings of about 3 per cent. less than the normal without oscillation for the same velocity of translation.

(ii) *Oblique Velocity.*—In connection with the ordinary use of Price meters swaying from a cable, oblique velocity tests are hardly applicable. However it may be well to quote some in order to show the magnitude of the errors which may arise when the Price meter is used on a rod.

In some experiments made by Rumpf a series of ratings were made with the meter inclined at various angles in a horizontal plane to the direction of flow.[39]

The Price meter when turned with its head to the left had its revolutions increased, but when turned to the right had them diminished, doubtless on account of the interference of stream lines through the yoke of the meter.

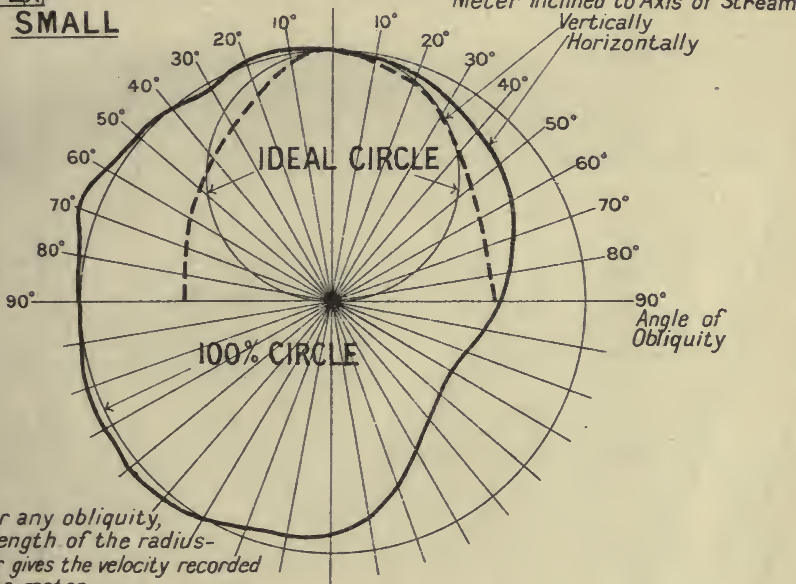
In another series of tests (Brown and Nagler)[3] made on both large and small Price meters, the meter was supported in the centre of a stream of water 14 inches deep flowing with a very constant velocity of 4 feet per second in the bottom of a 40 inch pipe. The meter was fixed on a cranked support so that it could

TESTS ON PRICE METERS

BROWN & NAGLER 1913. (Proc. Engrs. Soc. W. Penna Vol. 30 p415)

In water moving at a velocity of 4 ft/Sec.
All velocities in terms of axial velocity.

FIG. 2(A)
SMALL



NOTE For any obliquity, the length of the radius-vector gives the velocity recorded by the meter.
The true normal component is given by the radius-vector to the "Ideal Circle"

FIG. 2(B)
LARGE

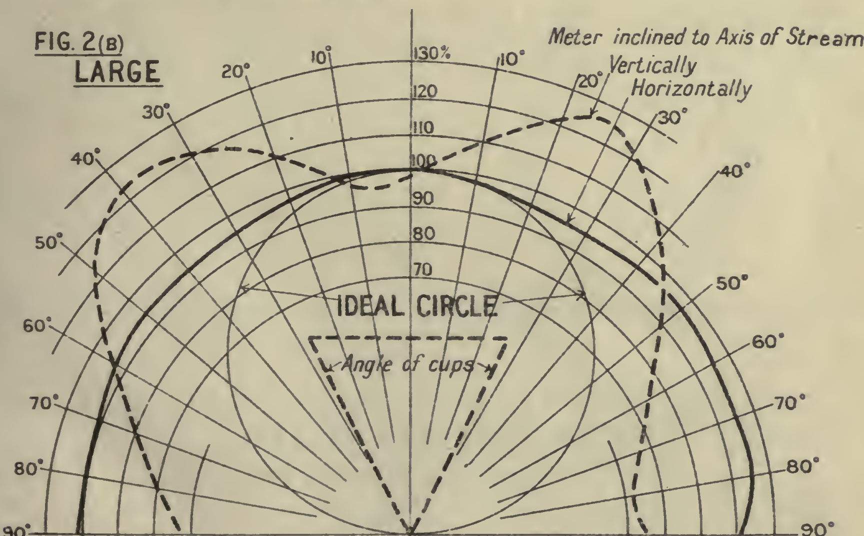


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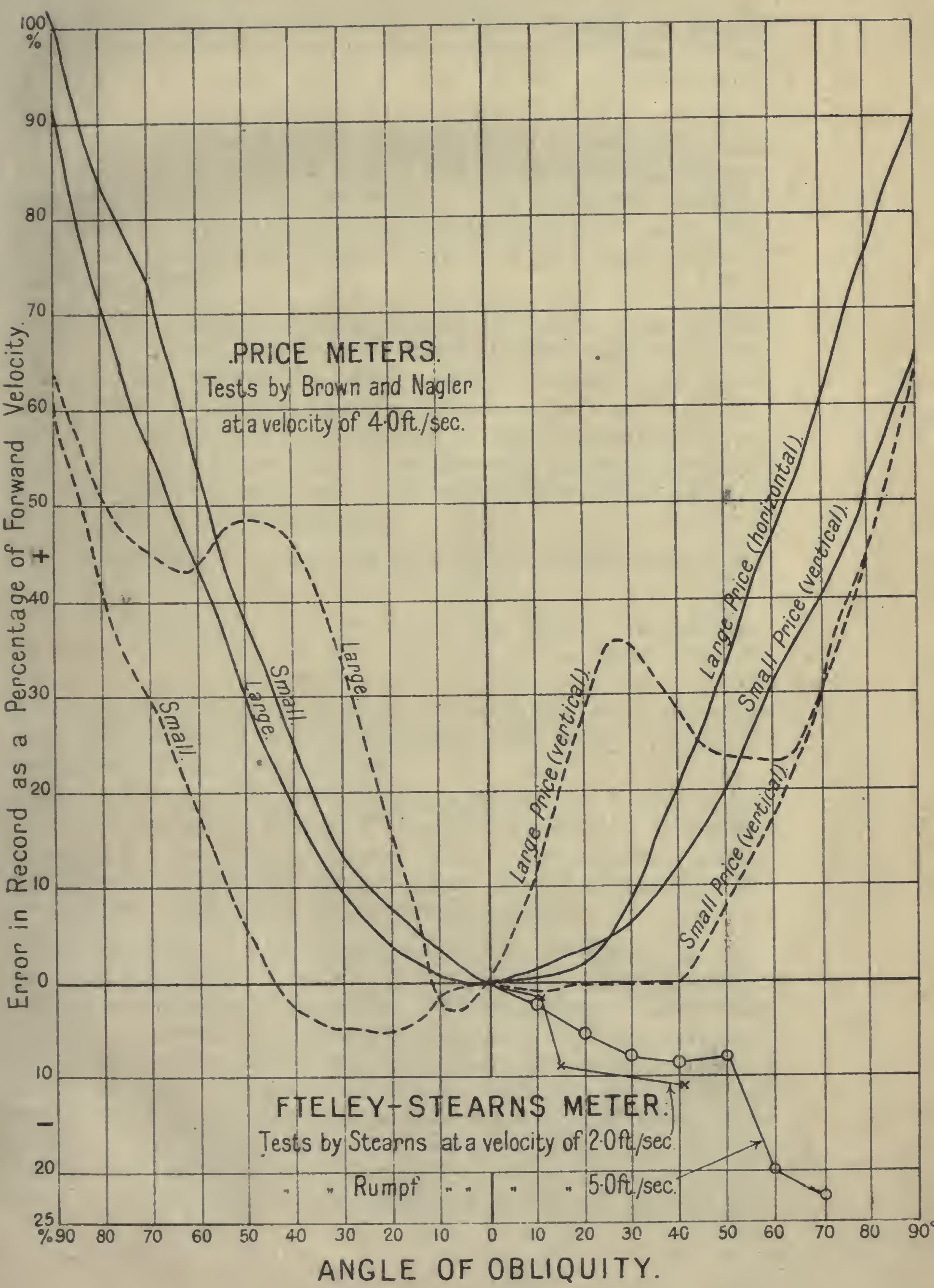
FIG. 3.

EFFECT OF OBLIQUE VELOCITY ON PRICE AND FTELEY-STEARNS METERS.



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be moved 90° in any direction. On tilting the large Price meter slightly above or below the horizontal it was immediately noticed that the revolutions increased very rapidly to a maximum, when the angle of tilt corresponded to the angle of the bucket, the excess being then about 25 per cent. over that in the horizontal position. On proceeding to the 90° position, when the axis of the meter is parallel to the line of flow, it was expected that the meter would either reverse or show little velocity. Actually it showed rather more than half the number of revolutions that it had registered in its normal position, and in the same direction. (Fig. 2*b*.)

The small Price meter (Fig. 2*a*) gave much better results. For inclinations up to about 25° either side of the horizontal it gave practically true horizontal components. For horizontal velocities, both types of Price meter record practically 100 per cent., irrespective of direction save where the frame of the meter introduces a sheltering effect.

In making ratings of Price meters in 1906 from a tug passing along a still water branch of a canal, Dowson[8] observed that when the tug rolled, the rating became irregular, the meter always registering excess velocity. An analysis is given of the extra distance travelled by the meter when it is executing vertical oscillations. To this extra distance the error was attributed and the actual observed errors were of the same order (10 per cent.) as the value obtained by calculation.

A similar result was obtained by American workers about the same time.

These experiments are in themselves rather inconclusive, but they indicate that on the whole the Price meter must be expected to give exaggerated results in turbulent water. However, it is so difficult to correlate the conditions in a turbulent river with those of the experiments that direct volumetric measurements are of more value.

The earliest experiments were carried out for the United States Geological Survey at Cornell University in 1903.[31] Here the discharge was measured in a canal 16 feet wide and the quantity flowing past run over the standard weir. The discharge over the standard weir was deduced from Bazin's formula.

The velocities of flow ranged from 0·23 to about 3 ft. per sec. At the higher velocities the water was much disturbed, large waves forming on its surface. The results go to show that when the conditions are favourable, the small Price meter, using the ordinary point method with one observation lasting 50 secs. to every 2·3 sq. ft. of area, will give the discharge of the Cornell canal with an accuracy of not less than 1 per cent. with velocities exceeding 1·5 ft. per sec. For velocities less than 1·5 ft. per sec. the discharge found by the Price meter is less than that by the standard weir, and this difference rapidly increases as the velocity diminishes.

The experiments carried out at Aswân recently described at the Institution of Civil Engineers may be summarised as follows.[29]

Experiments on the discharge of the sluices of the Aswân Dam have made it possible to measure the low water flow of the river with an accuracy of within about 1 per cent. The co-efficient of discharge for a certain type of sluice was determined by allowing it to discharge into a tank for a measured time. With appropriate corrections for the quantity of water passed during the opening of the gate and for leakage from the tank before measurement, the volume of water in the tank enables the co-efficient of discharge of the sluice to be calculated. The flow from a number of these standardised sluices was used to calibrate the stage discharge curve of the Aswân Gauge 4 miles down stream. This discharge scale was then used to measure the discharge of the types of sluice on which tank experiments could not be carried out.

By proceeding in this way it has been found possible to calibrate all the sluices through which the low water flow of the river is passed, and thus the discharge of the river can be measured by semi-direct methods with an accuracy of about 1 per cent.

Comparisons have been made between the discharge as measured by current meters and by the sluices. The meters employed were of either the medium or the small Price type.

Close to the sluices of the dam, where the water was so turbulent as to threaten to swamp a boat, discharge up to 17 per cent. in excess of the true value as determined by the sluices were given by a current meter.

" The systematic gaugings made further down stream where a fairly good discharge site was available show that there is no systematic difference of any importance between the measurements made by the meter and by the sluices."

16. Screw Type Meters in General

Under this heading are classed all meters with a horizontal axis of rotation. The nature of the rotating element is the principal item in which the various meters differ. In some meters it is a long two-bladed screw, while in others it is shorter and possesses more numerous blades. All the meters used on the Continent of Europe are of the screw type and the Haskell meter is extensively used in America. Among the principal makes of screw meter may be mentioned Amsler and Stoppani of Switzerland; Richard, France; Ott, Bavaria; Fteley-Stearns and Haskell, America.

The modern screw meters are directly developed from the first current meter made by Woltmann about 1790. This meter possessed a pair of flat blades and recorded their revolutions on a system of gearing. In 1847 a very important paper on River Gauging was read before a meeting of the engineers of the Ponts et Chaussées by Baumgarten describing his work on the Loire.[1] This contains a discussion of the Woltmann meter and gives the results of many tests, in consequence of which a new meter was designed in which the blades were given a helicoidal profile and increased to four in number.

The introduction of the electrical recording system is due to another French engineer. In 1859, when engaged on a survey of the sub-surface currents of the Bosphorus, Ritter constructed a meter which indicated its revolutions by means of an electrical signal which deflected a galvanometer needle.

The shape of the blades of the screw type meter is of vital importance. Nevertheless, it has received very little attention in published discussions of screw meters. It is not difficult to lay down a number of necessary conditions which the completed blade must fulfil, but these are insufficient to determine its shape; this has usually been done empirically. Working on the results of Baumgarten and others, in 1877, Kvassay published a valuable theoretical discussion of the question.[25] He set out to design a screw which would make the same number of revolutions per unit length of water passing at low as at high speeds. Existing screws made a low number of revolutions at low speeds, and the revolutions increased with the speed. This was attributed to displacement of the centre of pressure on the blades caused by inequality in pressures on adjoining portions of the surface. In order to prevent this difference in pressures on different portions of the blade and the resulting shift in the centre of pressure with change in velocity, it is necessary that the pressure be uniform all over the blade. Considering the case of a thin blade, Kvassay showed that, if the pressure on the blade is to remain uniform its surface must be so constructed as to satisfy the equations: $\frac{x}{x_1} = \frac{r^2}{r_1^2}$ and $\frac{\tan a}{\tan a_1} = \frac{r}{r_1}$ where x, x_1 are the widths of the blade at distances r, r_1 from the axis and a, a_1 are the angles between the tangent planes to the blade surface, at radii r, r_1 respectively, and the axis of rotation.

Tests recently made in Germany,[48] show that the results of this analysis are not borne out in practice. A number of screws were tried which varied in the shape of their traces on the circumscribing cylinder. The theory above given indicates that this trace should be a straight line, but the tests proved that the straight line gave a screw inferior to that given by a curve. A cycloid, hyperbola and parabola were tested and the latter gave best results. That is to say, the parabolic screw commenced to move at a lower velocity, and the relation between revolutions and distance became constant at a lower velocity, than in the case of the other shapes of screw.

With the exception of the Haskell and large Ott meters, all modern screw meters are used on a rod. Two methods of mounting are adopted, namely, the standing rod used by Harlacher and the suspended rod used by Dr. Epper of the Swiss Hydrographic Service. The use of the standing rod is practically confined to Germany and Austria, although it is by no means universally used even in those countries. The rod is placed on the bottom of the stream, and the meter slides along it, but is prevented from horizontal rotation by a rib or slot in the rod. The suspended rod method of mounting is more usually adopted. This method is exclusively used by the Hydrometric Surveys of France and Switzerland. Plate III shows a typical suspended rod meter outfit. The meter is fixed to the end of an oval steel rod which passes through a cast-iron angle bracket. This bracket is fixed to the floor of the bridge or platform from which the gauging is being made. The rod is prevented from sliding in the support by a spring grip which may be released by pressure on a pedal. The rod is graduated and thus serves to give not only the position of the meter but also the depth of the stream.

17. Amsler Meters

The 1915 model Amsler meter may be described as typical of the meters with a large two-bladed screw. There is some doubt as to the origin of this type of meter—it would appear that models were made in Hungary[16] and in America[18] about the same time.

The Amsler meter possesses a large two-bladed screw cast in aluminium. This carries with it a long steel axis, which is supported close to the head by a ball-bearing, and at the other end its thrust is taken up on a hard steel pivot, which bears on a sapphire. The axis carries a screw which meshes with a system of gearing and rotates a cam once in fifty revolutions of the meter. This cam allows a contact spring to make contact and so sends an electrical signal. The frame of the meter is in cast aluminium and is provided with a hole and clamping screws for use on a cylindrical rod of 1 inch diameter. A vertical tail is fitted.

Recently Amslers have developed a variant of this meter of much smaller size. Essentially it is similar to the 1915 model, but the diameter of the screw is only 90 mm. and the meter is made much more compact, the tail being omitted.

Amsler meters have been known for a very long time and have been used in many countries. At present the Government Hydrometric Services in France and Switzerland use some Amsler Meters.

18. Ott Meters

In pre-war days the meters manufactured by Ott at Kempten, in Bavaria, were used all over the world. The Surveys of Germany, Russia, France, Spain, the Argentine and Chile were the largest users. The meters are all of the screw type, but many different types of mounting were supplied. In Germany the standing rod, in which the rod is placed on the bottom of the river, and the meter slides along it into position, was most popular. For French use the suspended rod type of mounting was fitted. For use in deep and swift currents, several types of cable suspended meter were designed. One of these, typical of all, consisted of a length of tubing 2″ diameter which carried an ordinary screw current meter at its forward end and at its stern carried a bulb-shaped enlargement and a four-bladed rudder. The instrument was suspended from a universal joint, so placed that a quarter of the total length is placed before, and three-quarters behind, the joint. Meters of this type were always fitted with a ground contact plate to give notice of when the meter touched bottom. The whole instrument was about 5′ long and was made in weights ranging from 30 to 220 lbs. One meter of this kind was fitted with a "step-by-step" telegraph to indicate the angle (to 2 degrees) between the axis of the meter and the needle of a liquid compass fitted in the body of the meter.

An interesting modification fitted to some of the meters was the "Mensing-Ott" Patent Watertight-Contact Chamber. In this, the screw axis of the meter carried at its end a permanent magnet. This magnet rotated outside a sealed chamber within which it caused a light armature to revolve. The armature in turn drove an ordinary contact system by means of a worm and gear wheel. Since the contacts are made in a dry place all troubles due to electrolysis are avoided, but at high speeds the magnetic drive becomes unreliable due to slip.

Another useful device fitted to some of the meters was the "Back-Flow Indicator" designed by Dr. Epper. In gauging the discharge of artificial channels, such as turbine headraces, it is frequently found that at some parts of the cross section the water is flowing upstream in the opposite direction to the main stream. To allow of this state of affairs being made clear to the operator of the meter, the Back-Flow Indicator is fitted. This consists of a small flow-pendulum fitted in an opening in the tail of the meter. In normal flow this is deflected backwards and nothing happens, but when the flow is reversed the pendulum is pushed forward and makes contact with a contact pin, completing an electrical circuit which operates a warning device.

19. Stoppani Meters

Recently the manufacture of meters has been taken up at Berne by Stoppani. The meters are practically replicas of one of the Ott meters, above mentioned. The Swiss Hydrometric Survey have standardised the Ott meter with cylindrical guard ring and have persuaded the firm of Stoppani to make a similar instrument for their use.

The Stoppani meter (*see* Plate III.) consists of a frame in a vertical plane which carries the horizontal axis on two steel pivot bearings. The axis carries a three-bladed propeller and close to its other end has a worm thread cut on. The worm turns a gear wheel and commutator. The bars of the commutator are four in number, and it rotates once in each hundred revolutions of the meter. A contact spring rubs continuously on the commutator drum. By cutting out two or three of the contact bars, the meter may be arranged to give a signal every fifty or one hundred, as well as every twenty-five revolutions. The contact system is freely exposed to the water, a loose guard only being used to ward off large bodies. The propeller runs inside a guard ring of slightly conical shape, which serves both to protect it from shocks of floating bodies and to shield it from the effects of oblique velocities. Two sizes of the instrument are made, the smaller being used on a round rod, while the larger is supported by an oval rod of 2×4 cm. section. Stoppani also makes a two-bladed screw meter very similar to the Amsler 1915 model.

20. Richard Meters

Current meters have been made by Richard of Paris for a long time. However, the meters produced in pre-war days were of rather delicate construction and were not well adapted to the rough usage entailed in stream measurement. A new model has now been produced which is of much more robust construction. This is in its general features very similar to the 1915 Amsler meter. It is made not in aluminium but in bronze, and is thus considerably heavier than the Swiss instrument. Two screws are provided, one of four blades, for low velocities, and one with two blades for use at high velocities. The contact system provides for one signal every 25 revolutions. The meter is used fixed at the end of a steel rod of oval (2 by 4 cm.) cross section. This meter is now being introduced into the Service des Forces Hydrauliques in France.

21. The Fteley-Stearns Meter

The two chief types of screw meter of American origin are the Fteley-Stearns and the Haskell.

The Fteley-Stearns meter consists of a wheel with a number of short vanes running on a horizontal axis.[41] The wheel is provided with a rim in the form of a thin co-axial cylinder of a length equal to the length of the vanes. This cylinder fulfils two purposes : it strengthen the vanes and protects them from accidental damage and helps to throw off grass or other floating material which might cause a stoppage ; it also acts as a shield for the vanes against oblique velocities.

The meter as now made is provided with non-corrosive iridium bearings which are almost frictionless, the rear bearing being especially protected against dust and the like. The wheel is 5 ins. diameter, and has six vanes (the older pattern was $3\frac{1}{2}$ ins. diameter and had eight or ten vanes), the pitch of the wheel being 2·3 feet. The instrument is constructed to stand velocities up to 13 ft. per second. It is claimed that the instrument begins to revolve at velocities above 0·1 ft. per second, and is accurate above 0·2 ft. per second. An electrical recording device is fitted, but in the past a clutch and counting gear on the meter itself was usually employed.

This meter is always used supported at the end of a rod. As a rule its range of application is limited to the measurement of flow in artificial channels such as the large aqueducts of the water supplies of the cities of New York and Boston.

22. The Haskell Meter

The Haskell meter[18] is similar in appearance to the Amsler 1915 model previously described. Its screw, however, terminates in a conical head designed to act as a self-clearing prow for any débris in the current. The screw was designed so that the action of the current pressure on it should be integral and not differential. For work in large rivers and in the ocean a direction recorder has been fitted. This consists essentially of a compass needle so supported, in a chamber in the meter body, as to be free to assume the magnetic meridian at all times. This chamber is kept filled with oil, giving stability to the motion of the needle and preventing rusting. By means of an electrical circuit, the angle, to the nearest degree, between the direction of the meter and the magnetic meridian, is transmitted to a repeater or direction recorder in the boat.

The Haskell meter is always used swinging in gimbals and supported by a cable and kept down by a torpedo-shaped sinker. A two-bladed tail is usually fitted.

In America this meter has been used by the Mississippi River Commission. It has also been used by the Lake Survey to measure the discharges of the St. Lawrence, St. Clair and other large rivers.[42] In India the Haskell Meter has been used by the Indus River Commission.[4]

23. Tests on Screw Type Meters

The general discussion of desiderata leads to the conclusion that the screw type meter is most likely to give good results. It is now necessary to review the tests on existing meters to see if any of them approach the ideal. If the tests had been numerous it would probably have been advisable to treat of the tests on each meter in connection with the description of that meter. However, as the tests are very few it seems best to discuss all together.

(i) *Variations in Magnitude of Velocity.*—Tests of the effect of varying velocity have been made on the Fteley-Stearns meter. In testing the effect of velocity variations this meter was moved along on the rating car at a very irregular rate. (No more accurate description is given of this irregularity.) The number of revolutions per foot travelled was compared with the number obtained when moving the meter at the same mean velocity but with regular progression. The results show that the irregular motion always gives the greater number of revolutions. Under the conditions of these experiments, with a mean velocity of

3·0 ft. per second, the average positive error due to irregular velocity was about 4 per cent.[41]

Tests on Haskell and Ott meters were made by Groat at the Naval Tank of the University of Michigan. In this case the meters were subjected to oscillation during rating. On the whole it was found that the meters were retarded slightly by irregular velocity at all except the slowest speeds. When the velocity of oscillation became equal to about half that of travel the readings of the meter were increased by oscillation. The oscillations were made harmonically with a period of 10 seconds and amplitudes of one and two feet, and with a period of 5 seconds and the same amplitudes.[14]

(ii) *Oblique Velocity.*—Since the screw type meter is almost invariably used fixed in direction it should record only the axial components of oblique velocities, and hence tests on the effect of oblique velocity are of great importance.

The effect of oblique velocity has been studied on the Fteley-Stearns meter by two workers independently, and their results agree fairly satisfactorily.[39, 41] The meter was rated with its axis inclined at various angles to the direction of travel. The results show that, at the velocity used in the experiments (2·0 feet per second), the error caused by oblique velocity is slight [Fig. 3]. In other words, the meter records the forward components of oblique velocities with very fair accuracy, the error at an obliquity of 40° being only about 11 per cent. This small error must be in a great measure attributed to the influence of the guard ring in shielding the screw blades from oblique velocities to just the right degree.

In this connection it must be noted that the results of recent, as yet unpublished, Swiss work, show that, at least with some meters, the errors due to oblique flow are a function of the velocity as well as of the obliquity. Hence caution must be exercised in drawing conclusions from experiments made at only one velocity.

(iii) *Volumetric Tests.*—As previously noted in the case of the Price meter, volumetric checks of discharges measured by the meter are the best criteria of performance. Two sets of experiments, only, can be quoted : those of Stearns on the Fteley-Stearns meter and those of Murphy on the Haskell.

The experiments on the Fteley-Stearns meter were carried out in the Sudbury aqueduct of the city of Boston.[41] In this case the discharge measured by current meter was re-measured on a standard sharp-edged weir. This weir had previously been calibrated by direct volumetric measurement, a blocked section of the aqueduct being used as measuring chamber. Discharges were measured by the point method and by integration. The conditions were very favourable to experiments, in that the water supply could be kept very constant. Using the point method, which should give the best results as it more nearly approximates to the conditions under which the meter had been rated (velocity

2-3 ft./sec.), it was found that the discharge by the meter agreed very closely with that measured by the weir, the maximum deviation being an excess, meter over weir, of 1·2 per cent. There did not appear to be anything in the nature of a systematic deviation between the two methods.

With the integration method it was found that unless the velocity of traverse motion of the meter was less than one twentieth of the velocity of the stream ($\cdot05 \times 3\cdot0 - \cdot15$ ft./sec. say) the indications of the meter were much reduced.

Murphy's experiments on the Haskell meter were carried out at the Hydraulic Laboratory of Cornell University for the United States Geological Survey.[31] Here the discharge was measured in the canal by a Haskell meter and checked by passing over a standard weir. The conditions of flow in the canal were more regular than those obtaining in ordinary river channels, and hence a higher degree of accuracy was maintained than would be feasible in river work.

At velocities exceeding 1·5 ft. per sec., it was found that discharges measured by current meter agreed within 2 per cent. with those measured by the standard weir. For velocities less than 1·5 ft. per sec., the discharge given by the Haskell meter was greater than that of the weir, and the difference between them increased as the velocity diminished. This difference amounted to 6 per cent. when the velocity was 0·75 ft. per second.

IV.—COMPARATIVE TESTS OF METERS IN TURBULENT WATER

24. Tests at Massena, New York

In considering the effects of turbulence on meters, notice must be taken of the very extensive series of tests carried out at Massena, N.Y.[12, 14] These tests were made in connection with trials of new turbines and a very high degree of accuracy was obtained. Owing to the high velocity and turbulence of the water, the conditions were most unfavourable to current meter work, so much so that the engineers of the U.S. Geological Survey refused to co-operate in the tests.

In the most recent of these tests, discharges of 1,500 cubic feet per second had to be measured. Chemical methods were developed which gave a higher degree of precision than could be attained with the meters. However, it was found that if meters of different, but properly related types, be used simultaneously, results within about 1 per cent. can be obtained even under very unfavourable conditions.

The following propositions were established, and formed the ground work of the method of testing :—

"When a cup meter is run in turbulent water it will register a larger number of revolutions than a still water rating would indicate.

"When a screw meter is run in turbulent water it will register a smaller number of revolutions than a perfect still water rating would indicate.

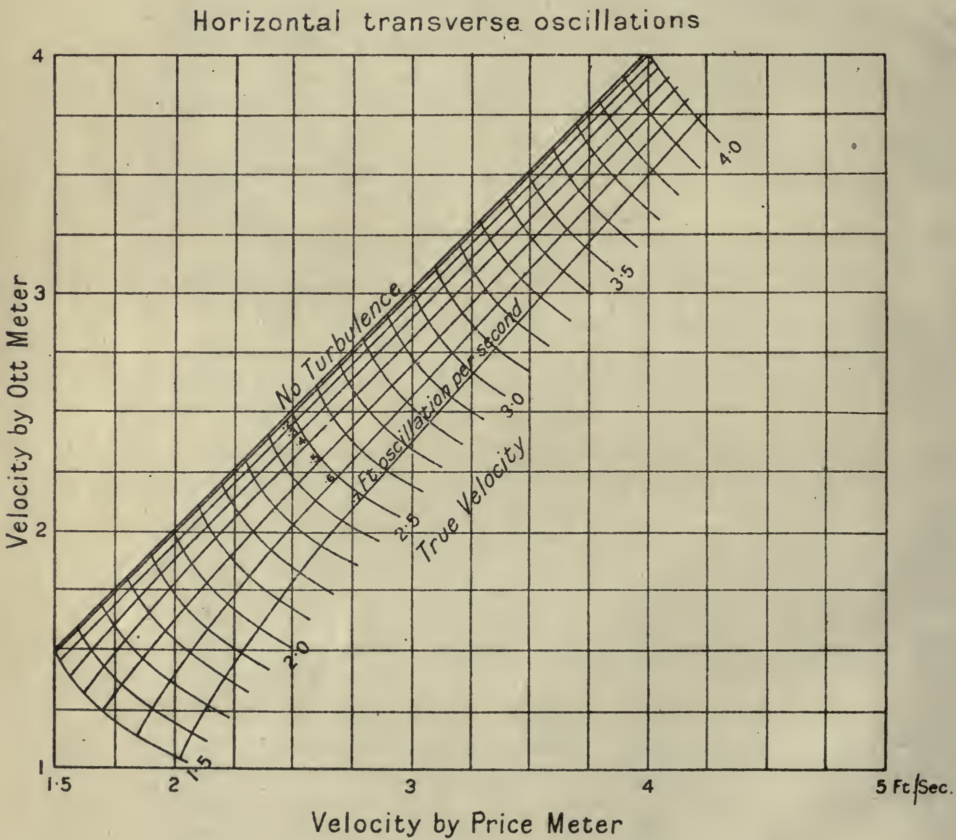
"If both types of meter are used simultaneously in turbulent water, the disparity between the discrepant velocities thus determined by the still water ratings may be taken as a basis for correcting the discrepant velocities."

Five meters were used in these tests—two large Haskell meters, two by Ott, and one small Price. They were rated at the Naval Tank at the University of Michigan in still water, both with and without oscillation. The meters had their tails removed and were rigidly fixed to oscillating arms capable of motion in three directions, longitudinal, horizontal-transverse and vertical-transverse. Three meters were thus rated simultaneously, the three arms oscillating in unison and the meters pointing in the direction of motion of the car.

In computing rates of discharge from current meter observations, certain assumptions have to be made. The usual assumption is that the meter performance is the same in turbulent as in still water. In this series of tests, it was assumed that both horizonal-transverse and vertical-transverse oscillations of the meters during rating represented horizontal and vertical disturbances in the meter section during the actual discharge observations.

COMPOSITE RATING DIAGRAM
TRUE VELOCITIES
Determined by OTT and PRICE METERS

Groat "Chemihydrometry." Trans. Am. Soc. C.E. 1916. Vol. 80. p. LII.



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The effect of longitudinal oscillations was comparatively slight, and hence it was assumed that the effect of longitudinal pulsations or perturbations of velocity in the meter section was also small. Roughly speaking, at velocities of from 2 to 5 ft. per second the error caused by oscillations at a velocity of 0·25 ft. per second in the record of a Haskell meter was about 4 per cent., so that for ordinary work the effect is not negligible.

In using this differential method it is advisable to use two meters, one of which is accelerated, and the other retarded, by the turbulent flow, in order that the combination may be as sensitive as possible. It would facilitate matters very considerably to have meters each of which suffers equal deviations for equal degrees of either type (horizontal or vertical) of turbulence. The screw meters are of this kind, but as both are retarded they cannot be paired. On the other hand, the Price meter which is, on the whole, accelerated is differently affected by horizontal and vertical impulses. This necessitates the estimation of the amount of either type of turbulence present before the record can be compared with that of a screw type meter.

From the results of the rating experiments, composite rating curves were prepared for a pair of meters. These are diagrams which will give the true velocity at a point from two velocity readings taken at this point by two different meters. (Fig. 4).

The true velocity may be read from the curved scale by locating a point on tne diagram opposite the velocity by one meter and over the velocity by the other meter, both velocities being based on the still water ratings, thus representing the coordinates of the point on the diagram. In constructing this diagram from the results of the oscillating ratings on the Price meter, it was assumed that the disturbances were equally distributed between the horizontal transverse and the vertical transverse directions.

That the conditions were exceedingly bad for meter work is shown by the fact that along one of the verticals the transverse velocity was upwards of one-half of the forward velocity (indicated by the discrepancy between the Price and Haskell meters).

V.—CURRENT METERS FOR LOW VELOCITIES

25. Examination of Existing Meters

Great importance attaches to the accuracy with which a current meter is able to measure low velocities of flow. In river gauging, low water flows usually require more accurate determination than flows of greater volume. In irrigation or drainage channels, the material forming the banks and bed frequently restricts the velocity of flow to a low value, but, nevertheless, accurate measurement of the discharge is essential.

The ideal meter would work like a wheel running along a rail, *i.e.*, it would make the same number of revolutions per unit of length of water flowing by, irrespective of the velocity at which the water passed. Ordinary meters, however, suffer from the effects of fluid friction on their blades, and from bearing friction. Hence very considerable slip takes place when the velocity of flow is low. The slip has also been attributed to displacement of the centre of pressure of the blade surface.[25] This dies out as the velocity rises, until, when the velocity reaches a certain value, the revolutions per unit distance become constant and independent of the velocity.

For accurate work it is essential that the revolutions of the meter should be close to their constant value at the velocity which is to be measured.

In a recent article Messrs. Fortier and Hoff, of the United States Bureau of Public Roads, Irrigation Division, have reviewed the various existing meters with a view to deciding which was best suited for measuring low velocity flows.[11] The curves, reproduced from that paper, show the number of revolutions made by the rotors of the various meters per foot of water flowing past at various velocities. [Fig. 5]. The curve for the ideal meter would be a horizontal straight line, showing that the meter responded even to the lowest velocities without any slip. For ease of comparison the diagram has been replotted on a percentage basis. [Fig. 6]. The number of revolutions made per foot by the meter at high speeds is taken as 100, and the revolutions at lower speeds plotted as percentages of this number. This diagram brings out very clearly the advantages of the small Price meter in this respect. Motion commences at a velocity of about 0·25 ft. per second, the revolutions then being 89 per cent. of those at high speed, while at 1·0 ft. per second the revolutions have attained their high speed value.

26. The Hoff Meter

The Hoff meter No. 2 seems to be even better than the small Price for measuring low velocities. This is an instrument designed in the light of the tests on the other meters.

FIG. 5.

STARTING VELOCITIES

Fortier and Hoff. Eng. News. Rec. 11·XI·20. Vol. 85. p. 923.

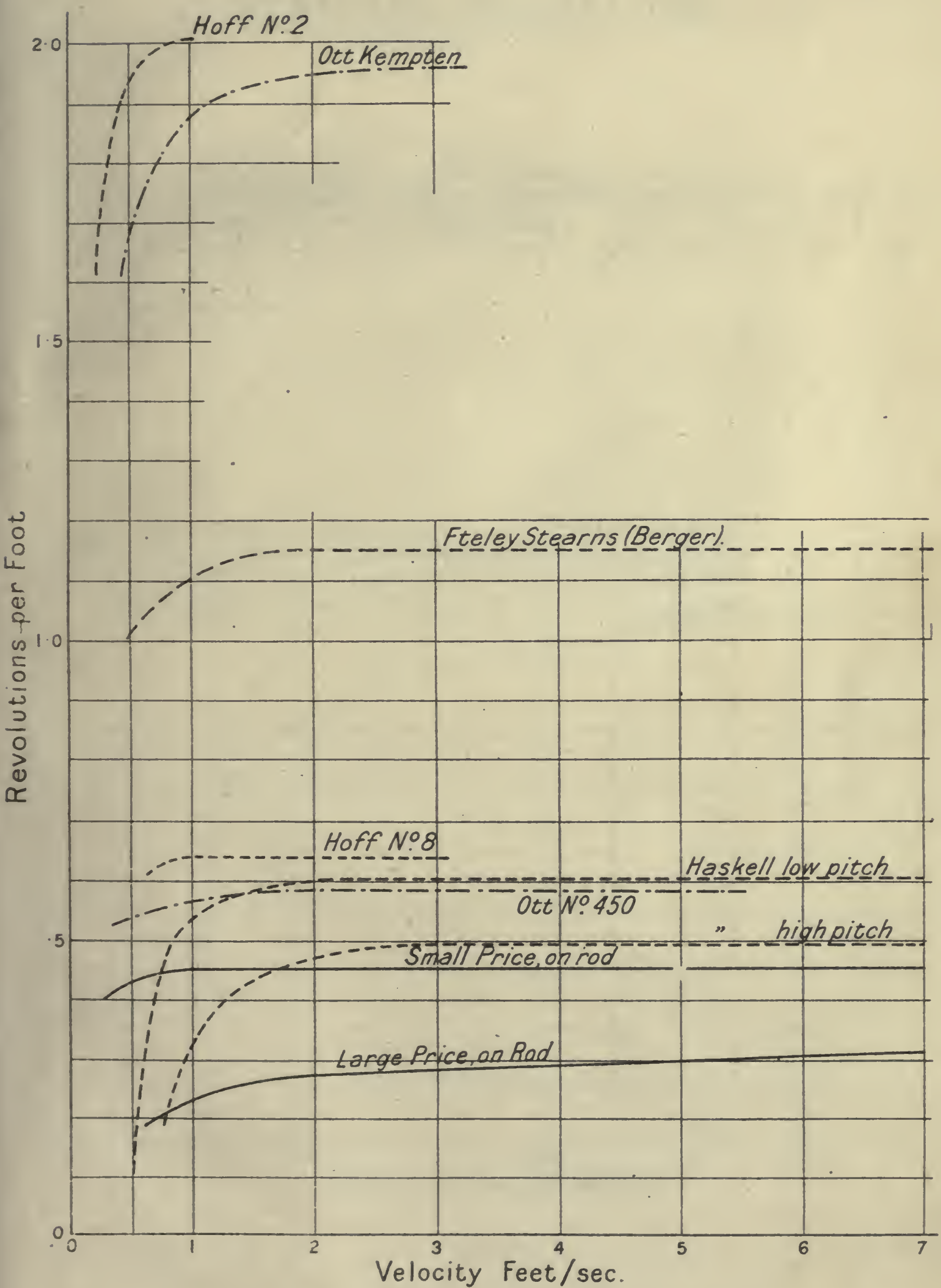

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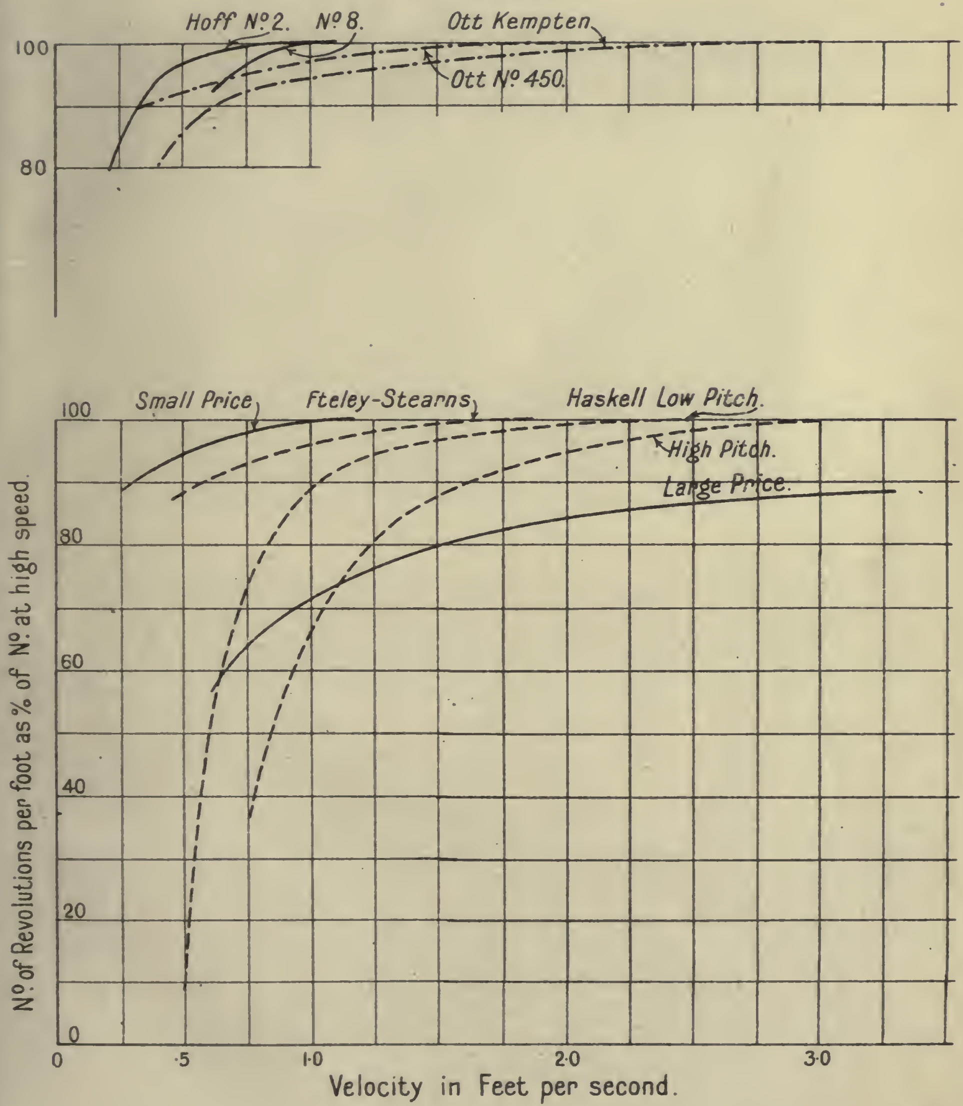
FIG. 6.

STARTING VELOCITIES.



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MEASUREMENT OF VELOCITY BY AN ELECTRICAL METHOD.

Curves showing increase in Resistance with increase of Velocity for different electrodes.

(Scientific Am. Supplement 2nd. Feb. 1917.)

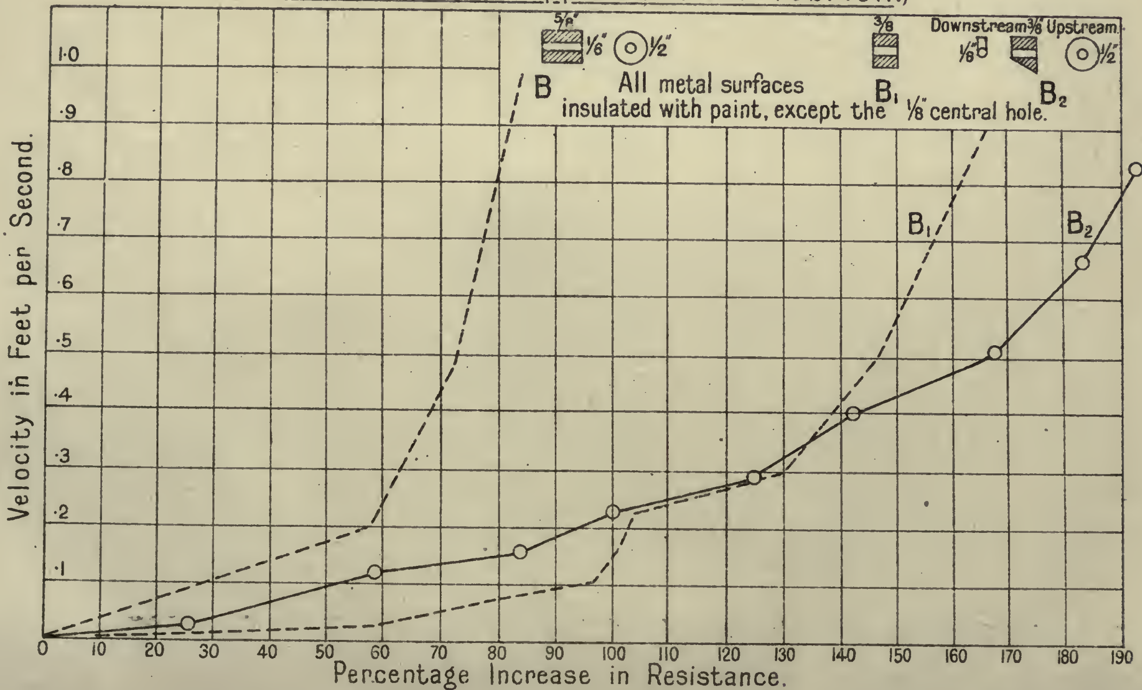

FIG. 7.

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It is intended for use in irrigation channels where velocities as low as 0·5 ft. per second must be measured with accuracy. It is fitted with a three-bladed propeller (about 3 in. diameter) designed to register only axial components of velocity. The frame is stream-lined so as to cause as little obstruction as possible to water flowing in a confined channel. Finally, instrumental friction is reduced to a minimum by making the moving parts of a material of the same density as water.

Save for the starting velocity tests, no further information is given of the behaviour of this meter.

27. An Electrical Method of Measuring Low Velocities

This method has recently been developed and tested experimentally in America. [*See* a paper by W. S. Cleverdon, Scientific American Supplement, 2nd February, 1917.] The fact on which it is based is that the resistance offered to the passage of an electric current between two electrodes immersed in a stream of water is dependent on the velocity of flow of the water. This is rather an unexpected result, but further experiments give a clue to its explanation. On separating the electrodes along the direction of flow, the resistance was increased for the same velocity, but the increase was not at all proportionate to the increase in distance. This observation at once suggested that the principal source of resistance was at the electrodes where the current passes into or out of the water. That this was the case was established by making experiments with electrodes of different shapes.

Many different shapes of electrode were tested. The results show that where the electrode is long and narrow and points in the direction of flow, so that it causes little eddying, there is little change in the resistance with increase of velocity, since the water keeps in contact with the electrode over its entire length. Where the electrode has a wide front and suddenly terminates, there is a tendency for the water to leave the rear face, forming a partial vacuum at this point, reducing the area of the electrode in contact with the water, and thereby increasing its resistance. The best type of electrode proved to be the inner face of a cylindrical tube, the ends and outside being insulated. Various proportions between the diameters and length were tried; the most efficient was found to be a $\frac{1}{8}$-in. hole in the centre of a brass cylinder $\frac{1}{2}$ in. diameter and $\frac{3}{8}$ in. long. The efficiency of this electrode was still further increased by chamfering off the rear portion of the cylinder.

With this type of electrode the relation between velocity and increase in resistance follows a very regular curve (*see* Fig. 7). The resistance may be used to measure all velocities up to about 1·0 ft. per second; above this the resistance becomes independent of the velocity.

The electrical method has the advantage that the very slightest movement of the water may be measured. Against this it must be noted that the resistance is sensitive to slight changes in the conductivity of the water corresponding to changes in quantity of dissolved or suspended solids. Further, any grease adhering to the electrodes will cause an enormous increase in the resistance. This, however, is a point which constantly requires attention when using a Pitot tube or a metal sharp-edged weir. The conductivity of the water may be taken into account by making tests at zero velocity before and during the experiments. The tests at zero velocity will not, however, take into account the effect of the coarser suspended matter, and further experiments are desirable on this point.

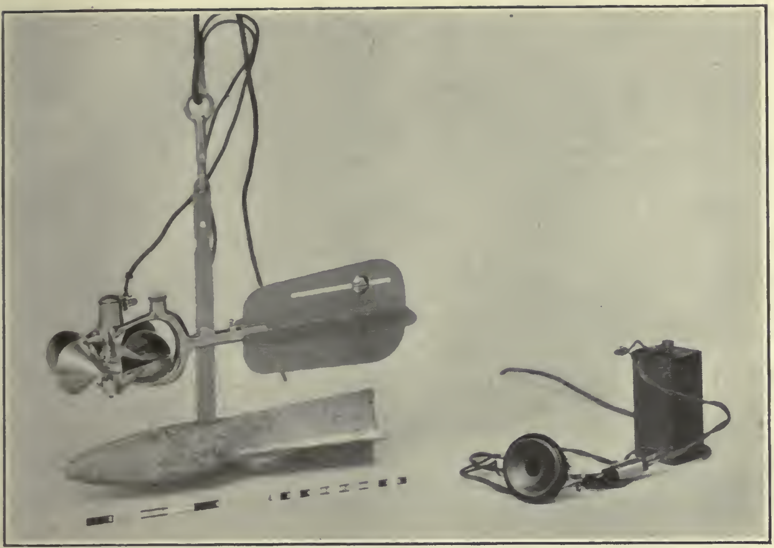
VI.—CONCLUSION

In reviewing the results of the tests on the different meters, the outstanding point is that under favourable circumstances most meters will give results of sufficient accuracy for river gauging.

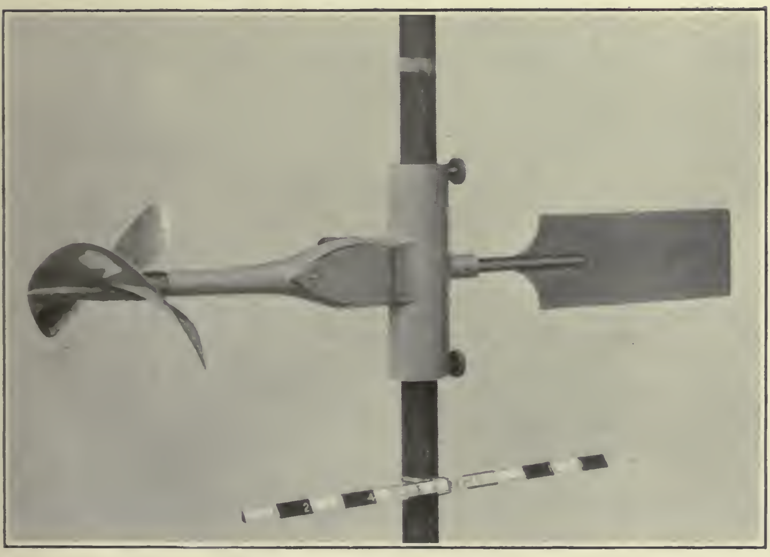
When the conditions are unfavourable and measurements need to be made in turbulent water, the crude results given by a single meter of any existing type are likely to be considerably in error. Dividing up the effects of turbulent motion into variations in magnitude and direction of velocity, it appears that the latter are much the more important. With the Price meter, oblique velocities cause over-registration, while with screw-type meters, they cause under-registration. This fact has been applied to the measurement of turbulent flow.

From a theoretical point of view there is no doubt that the best type of meter is the screw and that it should be used fixed on a rod. Either by giving the blades a special shape, or else by providing a guard ring, it is possible to make a screw meter give a very good record of oblique velocities. The main disadvantages attaching to this type of meter concern the supporting of the meter rod during measurement, and similar practical details. The Price meter, being used on a cable, is much more easily manipulated when conditions require that the measurements be made from a boat.

(*To face page* 30.)



I. Small Price Electric Current Meter, Model No. 623.—Showing meter with cable suspension, telephone and battery.



II. Amsler Current Meter, 1915 type.—Meter fixed on cylindrical rod.

(*To face page* 31.)

III. Stoppani Current Meter.—Showing meter attached to oval steel rod which is held by the cast iron support.

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