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BY

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VELOCITY MEASUREMENT OF AIR-WATER MIXTURES

BY LORENZ G. STRAUB,[1] M. ASCE, JOHN M. KILLEN,[2] AND OWEN P. LAMB[3]

SYNOPSIS

The search for an adequate explanation of the physical phenomena of natural occurrences is invariably held in abeyance by the lack of suitable measuring instruments and standards of measurement. Once accurate and detailed measurements can be made, the analytical treatment of a wide range of conditions is usually possible on the completion of basic experimentation. The insufflation of air into high-velocity streams of water in open channels is one of the many fluid mechanics phenomena still retarded in its complete analytical explanation by the inadequacy of instrumentation required for experimental observations. This paper traces the development and use of a velocity-measuring instrument at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, at Minneapolis. This instrument, referred to as the St. Anthony Falls (SAF) velocity meter, is particularly useful in the undertaking of velocity traverses in air-water mixtures.

INTRODUCTION

The capacity of high-velocity streams of water to entrap and contain large quantities of air is apparent in flows over spillways or down steep chutes. The "white water" produced by this air insufflation by open-channel flows is a heterogeneous mixture, varying in bulk density throughout the depth of flow and exhibiting pulsating density variations at all depths. The behavior of air-entrained flow as regards bulking, velocity, depth, and slope relationships, is important to the designing engineer. However, there is a meager supply

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of conclusive data on which to base quantitative estimates of these factors when design for freeboard and energy dissipation in steep-gradient structures is being considered. Typical patterns of air-water mixtures in high-velocity flows in open channels are shown in Figs. 1 and 2. Fig. 1 shows the water surface for flow in an inclined channel, and Fig. 2 shows the profile (through a transparent wall) of an air-entrained stream at a steep gradient. Both photographs were taken at speeds of 1/50,000 sec.

LABORATORY EQUIPMENT

The St. Anthony Falls Hydraulic Laboratory at the University of Minnesota, at Minneapolis, is uniquely suited for making high-velocity studies under favorable conditions. Large quantities of water are available at the natural head of 50 ft for the falls. Channels can readily be built to use the head and discharge under easily controllable conditions.

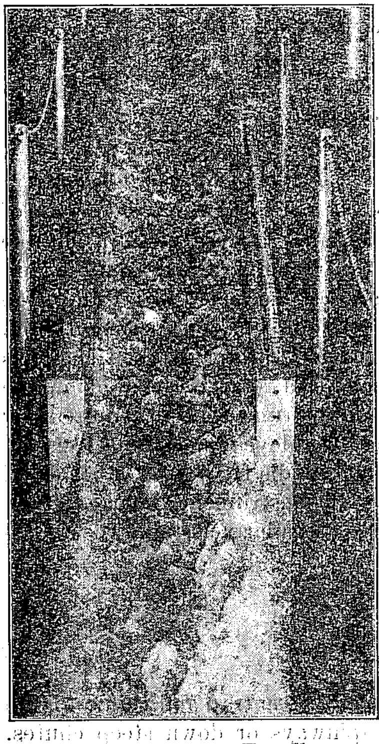

FIG. 1.—AERATED FLOW IN HIGH-VELOCITY CHANNEL

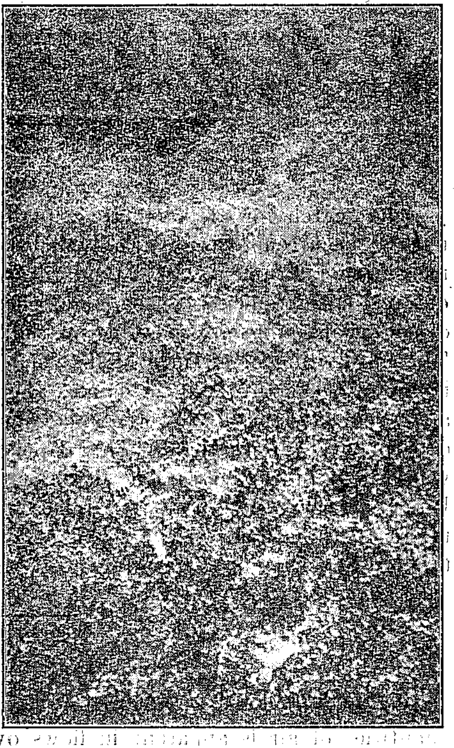

FIG. 2.—PROFILE OF AERATED FLOW

The first of these channels was constructed in 1940, in the turbine pit, at the St. Anthony Falls Hydraulic Laboratory, which is a large vertical shaft inside the laboratory walls extending from above the normal headwater pool elevation of the falls to the tailwater pool elevation. Both headwater and tailwater pools extend as canals into the laboratory. This air-entrainment test channel could be set at any slope from horizontal to 45° with the horizontal. The research program using this flume did not include detailed velocity measurements, but air-concentration traverses and photographic studies on this experimental setup proved to be invaluable in gaining an understanding of the air-entrainment problem and in developing specialized instruments for a subsequent, more comprehensive program.

A larger and more versatile air-entrainment test channel has replaced the earlier setup at the same location in the laboratory. The new flume is 18 in. wide, 12 in. deep, and 50 ft long, and can be set at any slope from the horizontal to the vertical. The design features of this channel will not be covered in this paper. However, the headbox design provides a region of uniform velocity at the inlet end of the flume which has proved useful for testing the velocity meters through a wide range of velocities.

Instrumentation has been incidental to the entire experimental program of aerated flow so that the sequence of steps leading to the St. Anthony Falls (SAF) velocity meter was supplementary to the studies using both the old and the new test channels. Intermediate models of the instrument were used extensively in the course of the experimental program before the later improvements were made.

A separate report has been issued by the St. Anthony Falls Hydraulic Laboratory in which the development of a separate instrument is described for use in measuring air concentration in flowing air-water mixtures.[4] The SAF velocity meter described in this paper is used in conjunction with the air-concentration measuring device to obtain detailed information regarding aerated flows. The functions of the two instruments are complementary, in so far as they are both needed in observations to define air-entrained flows completely. The two devices are completely self-sufficient; however, the accuracies and limitations of either instrument are independent of those of the other.

Studies and Instrumentation

A summary and bibliography of the literature relative to air entrainment,[5] assembled as an initial phase of the present investigations, reveals that the main experimental effort has been directed toward the determination of air content of flows. When velocity measurements were considered, they were usually used as a means for obtaining a better estimate of the bulk ratio of air to water in various flows under laboratory or field conditions. There are no precise data on velocity distribution in air-entrained flows that might be used in detailed analyses of shear distribution, energy loss, or other internal flow characteristics.

R. Ehrenberger, in pioneering studies of air-entrainment phenomena, assumed that the velocity distributions in the aerated test channel flows were linear between surface velocities obtained with floats and velocities measured

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[4] "An Electrical Method for Measuring Air Concentration in Flowing Air-Water Mixtures," by Owen P. Lamb and John M. Killen, *Technical Paper No. 2, Series B*, St. Anthony Falls Hydraulic Lab., Univ. of Minnesota, Minneapolis, Minn., 1950.

[5] "Air-Entrainment in Flowing Water, A Summary and Bibliography of Literature," by Owen P. Lamb, *Project Report No. 19*, St. Anthony Falls Hydraulic Lab., Univ. of Minnesota, Minneapolis, Minn., 1949.

near the flume bottom, where there was little entrained air.[6] With this estimate of the velocity distribution, Mr. Ehrenberger use a pitot tube to obtain air-concentration distribution in vertical traverses; the assumption being that any differences between the stagnation pressure to be expected at the assumed velocity and the stagnation pressure actually obtained were caused by the presence of air in the flow at the point of measurement.

With methods of measuring the air-concentration distribution directly by independent means, the question arises as to the feasibility of using the pitot tube to obtain applicable velocity measurements in conjunction with the data on air content. If the mixture of air and water were considered to be replaced at every point by a homogeneous fluid with a density equal to the bulk density of the mixture, the pitot tube could be used to measure the velocity. However, the mechanical function of the pitot tube involves the concept of a point or region of stagnation in the flow. It is necessary, therefore, to evaluate the possible difference in behavior between homogeneous and mixed flows in the vicinity of this stagnation point to weigh the applicability of the pitot tube in measuring the velocity of mixtures. In the case of points of flow where the volume of air entrained is small, the curvature of the streamlines at the end of the tube will cause separation of the air and water, as compared to the normal mixture. At higher levels of air concentration there occurs a succession of impingements against the end of the pitot tube in contrast to a stagnation point, and the validity of the measured values is doubtful. In addition to these and other inherently questionable features of the pitot tube, the accuracy of the velocity measurements would be limited to, rather than independent of, the accuracy of the air-concentration measurements.

The basic concept of velocity (distance divided by time) provides the most direct method for determining velocities in open channels. The oldest hydraulic techniques are based on this concept. Various float methods are used in river and canal velocity observations, in the form of surface floats, subsurface floats, rod floats, and other similar devices. A somewhat later development was the use of dye cloudlets over extended river stretches to determine mean velocities.

Salt-Velocity Method.—The salt-velocity method, introduced by C. M. Allen, for determining mean velocities and flow quantities by observations over long stretches of channels or conduits, marked an advance in measurements of this character.[7] Salt was substituted for coloring material in the injection techniques and then was detected by the passage of the salt cloud at some downstream station. This passage was recorded with an ammeter by an increase in conductivity between two electrodes placed in the flow at the downstream station. Various refinements and revised versions of this method were introduced by other investigators. Probably the most practical applications of this salt-velocity method were made in closed penstocks, pipe lines, and flow through hydraulic machinery for the purpose of establishing efficiencies of the hydroelectric plants. The Bureau of Reclamation, United

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[6] "Wasserbewegung in steilen Rinnen (Schusstennen) mit besonder Berücksichtigung der Selbstbelüftung," by R. Ehrenberger, *Osterreichischer Ingenieur-und Architektverein*, Nos. 15/16 and 17/18, 1926.

[7] "The Salt-Velocity Method of Water Measurement," by C. M. Allen and E. A. Taylor, *Transactions*, ASME, Vol. 45, 1923, p. 285.

States Department of the Interior (USBR), in a study of air-entrained flows, used the salt-velocity methods to obtain mean velocities in extensive reaches of high-velocity open-channel streams in flumes of constant cross section.[8] The velocity measurements were used to estimate the amount of air entrained in the stream.

SELECTION OF A VELOCITY-MEASURING METHOD

The mean velocity of flow through a cross section is readily computed in homogeneous fluid streams where the discharge and cross section can be determined directly. Even this basic information becomes inconclusive when air insufflation occurs because the air discharge and the cross-sectional area are uncertain. In fact, the data available to various investigators are so inconclusive that contradictory statements have been published as to whether the presence of entrained air results in an increase or a decrease of the mean velocity of flow.

In the design of a velocity meter, the range of conditions that might confront the instrument is important. Insufflation might be encountered in streams having a mean velocity as low as 4 ft per sec, but usually the velocities are much greater. Thus, the instrument refinements necessary for accuracy at low velocities are unimportant. At higher velocities, where air entrainment is common, the instrument must be rugged, positive in action, and sufficiently versatile to give a reasonable accuracy of velocity measurement throughout a wide aeration-density range.

The customary concept of fluid density, applicable to homogeneous fluids, is not directly applicable to heterogeneous fluid mixtures of macroscopic proportions. In considering the flow pattern of such a mixture, the filament is made up of random air-and-water regions. The concept of mean bulk density of the filament might be introduced for convenience, but not without discernment as to the limitations of this concept.

Extensive vertical traverses of air concentration conducted during studies at the St. Anthony Falls Hydraulic Laboratory indicate that the distribution of air concentration can be approximated by an equation of the logarithmic type when progressing from the flume bottom to the flow surface. Situations might arise in which the flow near the bottom of the stream is virtually devoid of entrained air, whereas near the surface the filament is almost 100% air. At lower levels of air concentration, where the volume of water exceeds the volume of air, the air might be expected to take the form of bubbles in the flowing stream of water. At levels where the mean air concentration is very high, it is to be expected that water droplets will be entrained in a moving stream of air. The transition between these two extremes from bottom to top provides a less clearly defined air-water mixture. Observations by means of high speed photography show other large-scale pulsating phenomena in the air-water flows. At some combinations of slopes and discharges, definite train-wave phenomena are superimposed upon the general air-entrainment pattern. Macroscopic air pockets may develop at some flow conditions, with

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[8] "Progress Report on Studies of the Flow of Water in Open Channels with High Gradients," by C. W. Thomas, *Hydraulic Laboratory Report No. 35*, Bureau of Reclamation, U. S. Dept. of the Interior, Denver, Colo., July 27, 1938.

the pockets extending far down into the flow. Some of these conditions are evident in Figs. 1 and 2.

This description of the general character of air-water mixtures produced by insufflation in open-channel flow of high velocity immediately directs attention toward the limitations of many customary methods of measuring velocity.

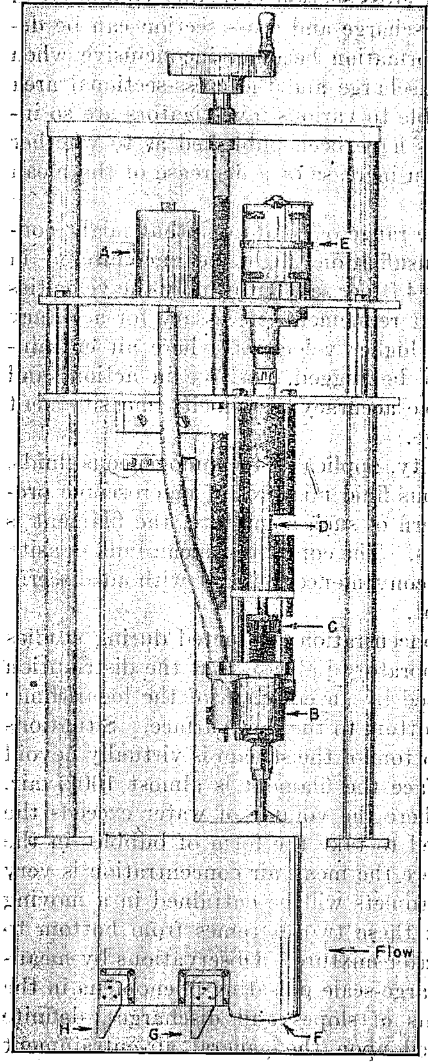
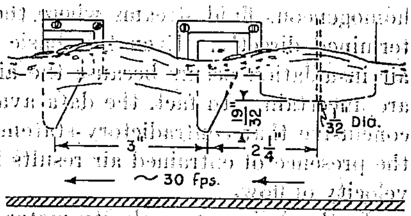
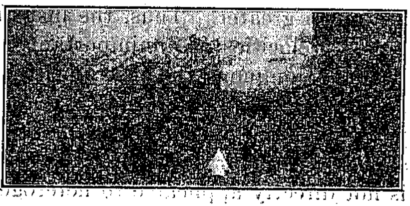


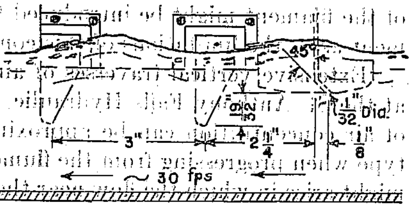
Fig. 3.—Probe and Injection System of SAF Velocity Meter



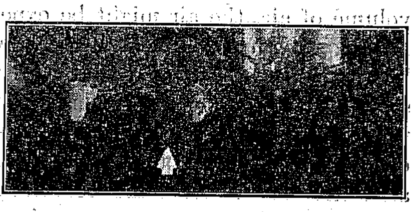
(a) Preliminary Nozzle



(b) Undesirable Cloudlet



(c) Final Nozzle



(d) Desirable Cloudlet

Fig. 4.—Design of Injection System and Nozzle

OPERATING PRINCIPLES OF THE SAF VELOCITY METER

The SAF velocity meter makes use of electronic methods for measuring very short time intervals that were developed extensively during World War II for radar, sonar, and other similar applications. The meter also makes use of the salt-velocity principle (which was initially applied to the measure of mean velocities over long reaches of channel) so as to minimize errors in the observation of time intervals. By measuring time intervals by electronics, the distance necessary to observe a velocity accurately can be shortened to such an extent that point velocities can be obtained and, accordingly, velocity traverses over a cross section can be made. Even turbulent pulsations can be observed by using very short distance intervals of measurement. The application of an instrument of such basic design for the determination of velocities in fluid mixtures can be checked against conventional instruments in homogeneous flows.

The operating principle of the SAF velocity meter consists basically of marking a small element of a flowing mixture, and then recording the time interval required for this marked element to traverse a fixed distance. The marking is accomplished by making a diminutive portion of flowing water more highly conductive to electrical current by injecting a very small amount of salt solution or similar electric conductor into the stream. The passage of this ionized cloudlet is then detected by electrodes at fixed stations in the flow path. The injection must be rapid enough to identify a very small portion of flowing fluid. The momentum of the injection must be low enough to avoid introducing a significant change in the velocity of flow.

Based on the foregoing principles, the SAF velocity meter combines a mechanical injection system with an electric timing and indicating system for the purpose of measuring velocities in air-water mixtures. The meter can complete the entire velocity measurement from the injection to the recording within a distance of 6 in. along the flow filament. The marking is done by injecting a miniature slug of 6% saline solution into the flowing stream within a time interval of less than 1/600 sec. The volume of each injection is approximately 0.03 cu cm, a quantity small enough to cause no significant momentum effects upon the flowing stream, although the velocity of injection is high.

The salt solution immediately ionizes the water particles that it contacts. An ionized cloudlet is formed which enters a filament of flow. The velocity of this filament is measured when the cloudlet is swept past the two electrode stations which are arranged in tandem along the flow path. Indications are transmitted to the electrical circuit when the front of this ionized cloudlet arrives at each electrode station. By making adjustments to the electrical circuit, the time lapse between the instant that the peak indication near the front of the cloudlet arrives at the first electrode station and the instant it arrives at the second station can be accurately measured. In the SAF meter, the distance between the electrode stations has been fixed at 3 in. Only the very tips of the electrodes are left uninsulated and exposed to flow.

In the development of the instrument, much experimental work was done in determining optimum conditions for the injection of the salt solution. The front of the cloudlet is of special importance because it must be both sharply defined and vertical, so as to assure sharp and accurate readings. This is accomplished by an abrupt and rapid injection using an injector pump from a diesel engine as the main component of the system. The injector pump is driven repetitively by a trip hammer, which is powered by a small electric drill motor. The salt solution to be injected is stored in a small reservoir and is gravity-fed into the injector pump. Metering of the quantity injected at each stroke of the plunger is possible because the pump plunger is slotted for variable delivery. For the open-channel aerated flows at the St. Anthony Falls Hydraulic Laboratory, it has been found that a rate of 15 injections per sec is most advantageous. At each stroke of the injector-pump plunger, the pressure is built up to a point at which it abruptly opens a spring-loaded valve in the outlet port of the injector. This valve closes immediately after the peak of the pressure pulse has passed. The fluid charge then passes through a small injection tube leading from the outward port of the injection pump to the point of injection into the flow stream. At the point of injection, the diminutive slug of salt solution in the end of the needle is abruptly forced out into the flow to form the ionized cloudlet, of which the passage is recorded at the electrode stations.

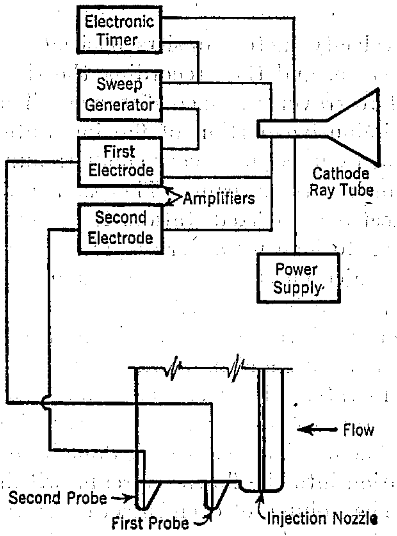


FIG. 5.—SCHEMATIC DIAGRAM OF ELECTRICAL CIRCUIT FOR SAF VELOCITY METER

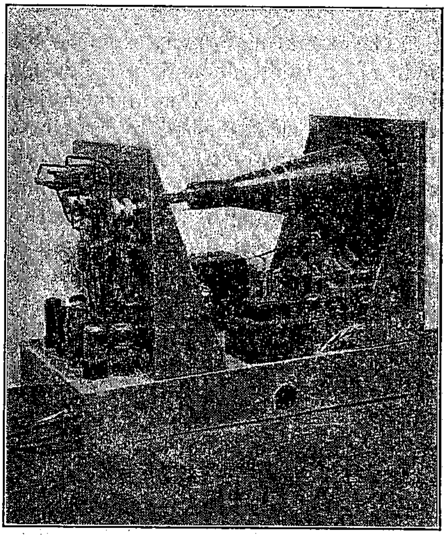


FIG. 6.—INDICATING AND TIME CIRCUITS IN UNIT CHASSIS

Fig. 3 shows the injection system. The salt solution from reservoir A flows down through the tube to the inlet port in the diesel injector pump B. The pinion C, which is attached to the pump plunger, can be rotated to set the proper delivery volume. The pump plunger is actuated by the trip hammer D, which in turn is driven by the electric motor E. The injection pulse from the pump is transmitted through the injection tube to the point of injection F.

If the injected slug encounters any water, its downward movement will be dissipated, and the small mass will almost immediately attain stream velocity. The ionized cloudlet in the water will then pass by the tips of the electrodes G and H, which are spaced 3 in. apart, and a velocity reading will be obtained. If the injected spray does not encounter any water, but is fired directly into an air pocket, the momentum of the injection will carry the salt solution down past the level of the electrode tips and there will be no indication. The spacings between the two electrode stations, the distance between the point of injection and the first electrode station, and the difference in level between the point of injection and the electrode tips were all selected so that the salt cloudlets that have attained stream velocity would be the only ones carried past both electrodes, thus forming indications for the meter.

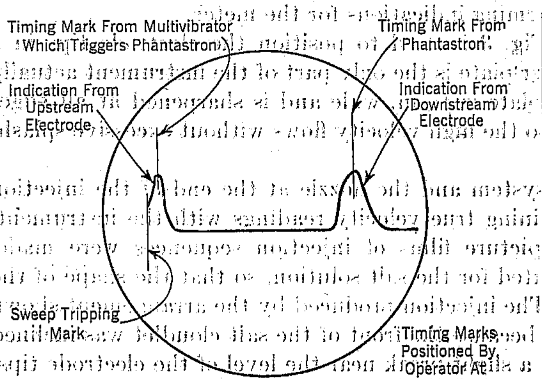
The threaded shaft in Fig. 3 is used to position the electrode tips in a vertical direction. The lower plate is the only part of the instrument actually inserted in the flow. This plate is ⅛ in. wide and is sharpened at all edges so that it can be inserted into the high velocity flows without excessive splashing.

Design of the injection system and the nozzle at the end of the injection tube proved critical in obtaining true velocity readings with the instrument. During the study motion picture films of injection sequences were made. Fluorescein dye was substituted for the salt solution, so that the shape of the cloudlet would be visible. The injection produced by the arrangement shown in Fig. 4(*a*) was undesirable because the front of the salt cloudlet was inclined with the vertical, and it had a slight break near the level of the electrode tips, as shown in Fig. 4(*b*). Since the front of the cloudlet is the point at which the beginning of the indication is relayed to the electrical circuit, this injection would tend to promote erroneous readings. Fig. 4(*c*) illustrates a desirable injection system, in which the salt cloudlet was compact and the leading edge was vertical, as shown in Fig. 4(*d*).

The electrical circuit is shown schematically in Fig. 5. The leads from each of the electrode stations in the probe are connected to the cathode-ray tube through their respective electrical amplifiers. The power supply and sweep generator circuits are necessary for the operation of the cathode-ray tube. The circuits are all enclosed in the chassis shown in Fig. 6. The electronic timing circuit is similar to a type developed for radar timing during World War II. The function of the electronic timing is to place marks on the cathode-ray tube screen at the beginning and at the end of each timing interval. Separate knobs on the electrical control panel allow the operator to position the limits of the timing interval at the peaks of the indications from the electrode stations. When the time-interval markers are positioned accurately on the indications from the electrodes, the reading on the phantastron dial on the panel can be directly converted into stream velocity. The phantastron dial can be set with extreme sensitivity as it has one thousand separate divisions on its 10-turn range. The timing circuit accuracy is on the order of ±0.025 millisec.

Typical indications which appear on the face of the cathode-ray tube are shown in Fig. 7(*a*). The marks showing the extremities of the timing interval are positioned at the peaks of the indications from the respective electrodes. Repetitive injections result in a succession of such indications on the cathode-ray tube screen. All the indications fall close to one another, but there are small differences because each indication represents an instantaneous sample of the longitudinal velocity at a point in the flow, and the flows in which the measurements are being taken are highly turbulent. At the rate of 15 injections per sec, the visual averaging of the small differences of the indication peak positions and proper positioning of the timing marks by the operator have given satisfactory results.

Fig. 7(*b*) is a motion picture strip of indications appearing on the cathode-ray tube from successive injections. The timing marks were not positioned on the peaks of the indications when these pictures were taken so that the independence of their spacing could be illustrated.



(*a*) GENERAL SKETCH

(*b*) PICTURE RECORD

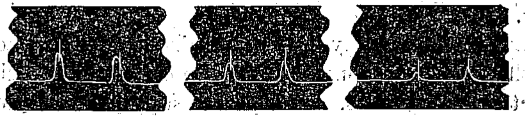


FIG. 7.—CATHODE-RAY TUBE INDICATIONS

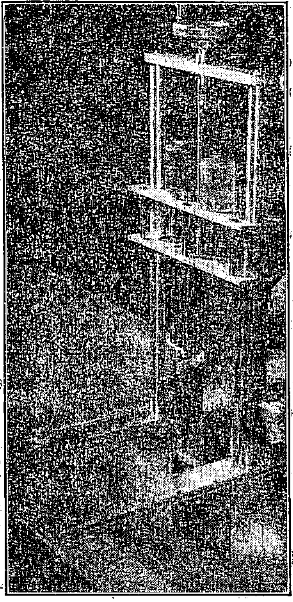


FIG. 8.—SAF VELOCITY METER MOUNTED FOR OPEN-CHANNEL MEASUREMENTS

Fig. 8 shows the SAF velocity meter with the probe elevated above the high-velocity flow. In operation each reading with the instrument requires about 2 min. This includes the time necessary for the operator to position the instrument in the flow, start the injection motor, observe the indications on the cathode-ray tube, position the timing marks, and read the velocity on the phantastron dial. The actual procedure can be readily learned, as the only adjustments necessary for determining the indicated velocity are the two timing marks.

The instrument is limited with regard to making accurate measurements close to the wall. The mounting permits it to be used as close as ⅜ in.

from the side walls; it is doubtful whether accurate readings could be obtained closer than this distance from the wall because of electrode interference set up by the steel-wall boundaries. When the point of measurement is closer than ⅜ in. to the bottom of the channel, there will probably be excessive interference with the injection cloudlets. Such interference would promote erroneous measurements.

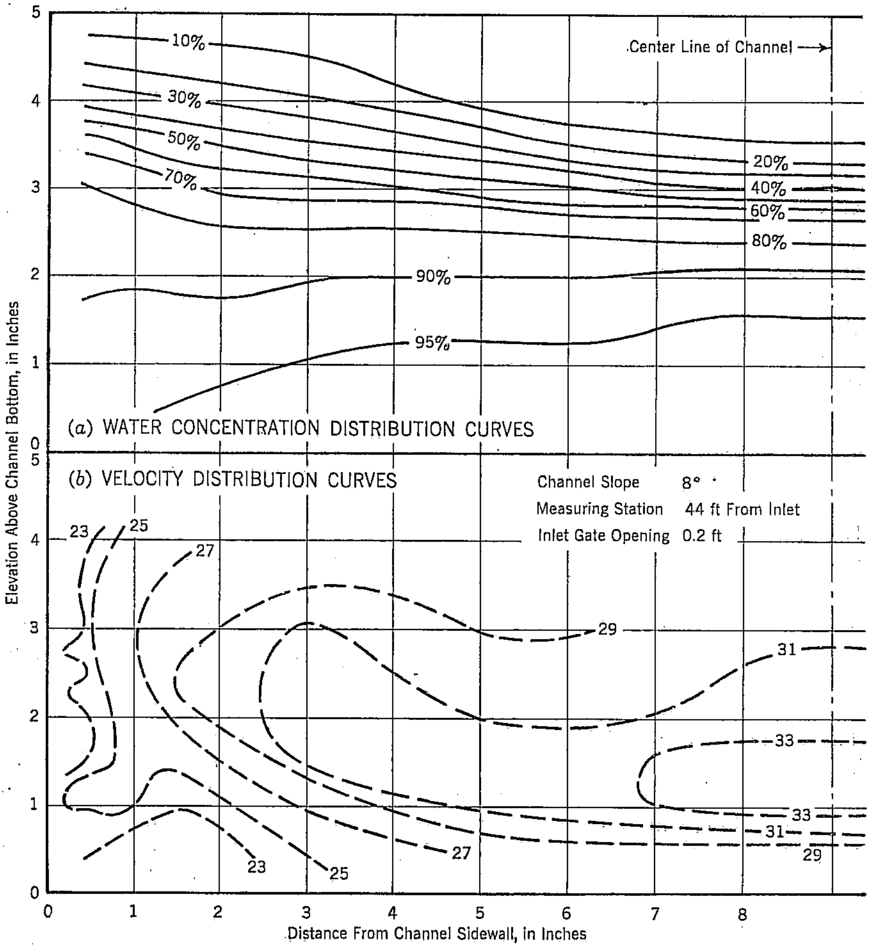


FIG. 9.—VELOCITY AND WATER CONCENTRATION TRAVERSES OF AERATED FLOW WITH SAF INSTRUMENTS

TEST VERIFICATIONS

Various experiments have been made to test the practicality of operation, the effectiveness, and the accuracy of the SAF velocity meter. The most direct check possible is a comparison with a pitot tube in a nonaerated stream. The velocities indicated by the SAF meter were found to be slightly lower than those obtained by the pitot tube at the same point and flow condition.

That is, nearly all points fall slightly below a line of perfect correlation. The apparent tendency of the SAF meter is to indicate velocities 1% or 2% lower than the velocities obtained by the pitot tube. This might be attributable to the velocity deficiency caused by the drag of the first electrode since the tips of the electrodes are the only obstructions in the flow at the level of the filament being measured.

In aerated flows, the instrument indicates a velocity reading when the injection slug comes into contact with a volume in the flow filament that has an appreciable percentage of water. There will be a sufficient number of indications as a result of repetitive injections to obtain mean-velocity determinations by the instrument at air-concentration levels of about 70% or 80%. Above the 80% level of air concentration, there are insufficient numbers of indications on the circuits to measure mean velocity because the water is mainly in the form of isolated droplets in the air flow. In the highly aerated regions of flow, no direct method of verifying the velocity recording of the meter is available, but the consistency of results and the reasonableness of the velocity patterns in vertical planes of the stream cross section establish the measurement reliability. The instrument may be used for measurements throughout the flow depth from points of low air concentration, near the stream bottom, up to the 80% level of air concentration.

A plot of the water-concentration distribution and the velocity distribution in an air-entrained stream is shown in Fig. 9. The experimental observations of the water-concentration distribution were obtained with the electric air-concentration measuring instrument developed at the St. Anthony Falls Hydraulic Laboratory, and the velocity observations were obtained with the SAF velocity meter. The two distribution plots define the air-entrainment and velocity patterns in the flow cross section.

The measured volume of water flowing through the channel shown in Fig. 9 was 10.95 cu ft per sec, whereas an integration of water flow in the cross section —both the air-entrainment observations and the velocity observations having been taken into account—gave a bulk discharge of water of 10.8 cu ft per sec. Thus, the bulk flow agreed with the integrated discharge to within 1.5%. This check must be considered fortuitous because the several uncertainties concerning velocities close to the solid boundaries, and near the indefinite free surface of flow, would appear not to warrant normal accuracies of the order of 1%. Reasonable assumptions concerning the water discharge in the boundary areas had to be made to complete the integration. However, the fact that the experimental observations can be correlated so closely illustrates the applicability of the instrument to the types of flow for which it was designed.

STATUS OF THE SAF VELOCITY METER IN 1951

The SAF meter has been mounted in a manner that will facilitate velocity traverses in the aerated open-channel flows being studied at the St. Anthony Falls Hydraulic Laboratory. The new mounting is shown in Fig. 10, in which the letters denote items which are the same as in Fig. 3.

The electrical circuits have been developed further, so that the placing of the limits of the timing sequence on the paths of the velocity indications is done automatically. The averaging of these indicated times is also accomplished by the electrical circuit, eliminating operator-judgment in placing the timing marks. Furthermore, the circuit dispenses with the need for the cathode-ray tube which was essential to the developmental phases of the instrument. This allows for more convenient packaging of the entire electrical circuit. The mean velocity is read directly on the meter, making the instrument entirely objective and simple to use in an experimental study.

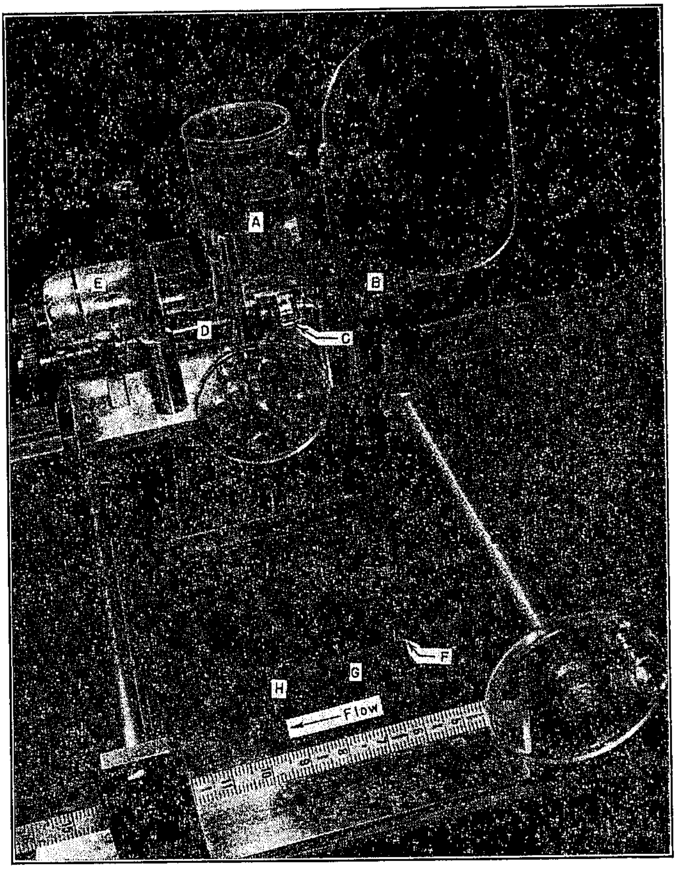


FIG. 10.—SAF VELOCITY METER MOUNTED FOR TRAVERSING LABORATORY OPEN-CHANNEL FLOWS

CONCLUSION

Incorporation of the injection tube and the electrode stations into a single plate proved a most satisfactory arrangement for a device that must be inserted into high-velocity streams. There should be little difficulty in constructing a similar probe on a larger scale for investigating aerated flows in large-scale field structures. The compact portable electrical system by which the velocities can be read directly on an electrical meter is particularly adaptable to field conditions.

The SAF velocity meter used with the cathode-ray tube is quite satisfactory for laboratory observations, and it delivers an individual reading accurately on the order of 2% of the actual velocity. It is quite sensitive to velocity changes and permits detailed study of aerated flows. Exploratory studies indicate that the instrument might be used for turbulence measurements in water. Its use for measuring velocities in other fluid mixtures is also possible under the proper conditions.

ACKNOWLEDGMENTS

The development of the SAF velocity meter is one phase of a comprehensive experimental and analytical investigation of air insufflation and air-entrained flows first undertaken at the St. Anthony Falls Hydraulic Laboratory, prior to 1943. This investigation was initially sponsored by the Engineering Foundation (United Engineering Trustees, Incorporated) and the committee on Research, Hydraulics Division, ASCE. More recently, the studies have been sponsored by the Office of Naval Research, United States Department of the Navy.