Methods of Flow Measurement in Well Bores

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1544-C

Prepared in cooperation with the Pennsylvania Geological Survey, Department of Internal Affairs, Commonwealth of Pennsylvania

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By EUGENE P. PATTEN, JR. *and* GORDON D. BENNETT

GENERAL GROUND-WATER TECHNIQUES

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ABSTRACT

Three techniques of borehole-flow measurement are particularly suitable for use in a water well: the brine-tracing method, use of the thermal flowmeter, and use of the Au current meter. Each of these methods was tested by the authors, and the results of these tests, together with certain general comments on the use of each method, are reported in this paper.

The brine-tracing method is the most troublesome to use, because both logging and brine-injection equipment must be in the well. It is unsatisfactory for measurement of flow at a single point in the well bore, or at a single instant of time; a finite time and depth interval are always necessary. The method is well suited, however, to a problem such as the measurement of very slow flow through a long interval of borehole.

The thermal flowmeter is a relatively new instrument, but tests indicate that its use holds forth the most promise for precise flowmetering in the future. The response of the meter is an electric current that is proportional to the flow velocity in the well bore, which makes it highly suited to incorporation into a well-logging unit. The thermal flowmeter tested by the authors gave reliable results in the velocity range from 2 to 75 feet per minute, and it is believed that with slight modifications in design, meters can be developed that will measure either higher or lower velocities.

The Au current meter has been used by the Geological Survey for many years, and is a convenient and fairly reliable instrument for measuring discharges in the range commonly observed in pumping wells. Its disadvantages include the fact that instantaneous recordings of velocity are not possible, and that the meter will not respond below a certain low velocity.

A brine-dilution technique that has been used successfully for pipe and channel flow is discussed also. The authors believe that this method might be modified, with the development of suitable equipment, to deal with borehole flow.

Seven other methods of flow measurements presently in use in the oil industry are reviewed briefly.

INTRODUCTION

This report discusses the results of an investigation of the methods for measuring the flow of water within a borehole. It represents one phase of an investigation into the application of borehole geophysics to hydrology that was made by the U.S. Geological Survey in cooperation with the Pennsylvania Topographic and Geologic Survey.

As the use of quantitative hydrologic methods has increased the need for accurate methods of measuring flow within a borehole has also increased. For example, a quantitative study of a well penetrating several aquifers has small value unless some means of measuring the discharge from each aquifer is available.

The increase in use of electric well logging in hydrology has also emphasized the need for such measurements, as the lithologic data provided by the logs becomes much more valuable if it can be correlated with flow data. Certain methods of flow measurement have been developed, moreover, which utilize conventional logging equipment; in addition, some flowmeters now in use separately will probably be incorporated into logging units in the future.

This report is not intended to be a comprehensive discussion of all types of flow measurement, as certain techniques have been described adequately elsewhere and, therefore, are treated only briefly here.

The authors conducted field tests of the brine-tracing method, the thermal flowmeter, and the Au current meter. In each case the borehole-flow measurements were made in the cased part of a well as the well was discharged at different rates. A gasoline-driven centrifugal pump was used, with the pump intake set well above the interval of measurement.

Independent determinations of the flow were made at the surface by measuring with a stopwatch the time required to fill a 55-gallon drum. In testing the brine-tracing technique the results of these surface measurements were compared with the flow rates computed from the tracing results. In testing the flowmeters the results of these surface measurements were used to construct calibration curves for the instruments. The merits of the instruments are discussed on the basis of the general characteristics of these calibration curves.

In the case of the thermal flowmeter the calibration curves obtained in field testing are supplemented by a set of curves obtained in the laboratory.

BRINE-TRACING METHOD

The brine-tracing method of measuring the movement of water has been used extensively in pipe and open-channel flow. Its use in borehole flow was a natural consequence of the introduction of fluid-conductivity logging equipment. It is hardly possible to say who first applied the technique—it seems to have come into use gradually, in a variety of places, without specific mention in the literature. However, U.S. patents were granted for such techniques as early as 1925.

The technique used during this investigation was to inject a discrete slug of brine into the flow and then trace its movement with the fluid-conductivity device. The flow velocity was then calculated from the time and distance intervals separating the two recorded positions of the brine slug.

INSTRUMENTATION AND EQUIPMENT

The equipment necessary for this method of flow measurement includes a fluid-conductivity logging apparatus, a suitable brine-injection device, and a clock or stopwatch for timing the movement of the brine. Most of the commercially available fluid-conductivity devices are satisfactory for this work. The primary requirements which they must meet are accurate depth control, and sufficient sensitivity to detect the brine.

The brine-injection device may take one of several forms and can usually be improvised in the field. The only requirement is that the device be capable of injecting a discrete slug of brine at the desired depth. The authors have used a device of the sort diagrammed in figure 1 by which air is pumped into the brine container by a small hand pump. The air, in turn, forces brine through a ¼-inch plastic hose to the desired depth of release. Once flow has been established in the hose the brine will siphon, and injection can be controlled merely by opening and closing the valve leading into the plastic hose.

Another device used by the authors consists of a cylindrical metal brine container whose ends are sealed with sheet gelatin. The container is not filled until immediately prior to measurement, as the sheet gelatin dissolves after being in contact with water for a short time. The device is suspended beneath the logging probe, and the probe and container are lowered to the desired depth. The probe is then moved up and down until a deflection of the fluid-resistivity log indicates that the gelatin has dissolved and the brine has been released.

Obviously, many other devices may be used for brine injection. Some workers have obtained successful results simply by suspending a bottle of brine beneath the probe and breaking it against the wall of the hole. Any method which is convenient may be used if a discrete and easily recognizable brine slug is produced.

THEORETICAL CONSIDERATIONS

In a cylindrical conduit of the diameter of a typical water well and at the flow rates commonly found in well discharge, the flow-velocity profile will generally have the form shown in figure 2. The velocity falls off rapidly near the wall, but maintains a fairly constant rate, v_m, across the middle of the conduit. Because the velocity v_m prevails over most of the cross-sectional area of the flow, the prob-

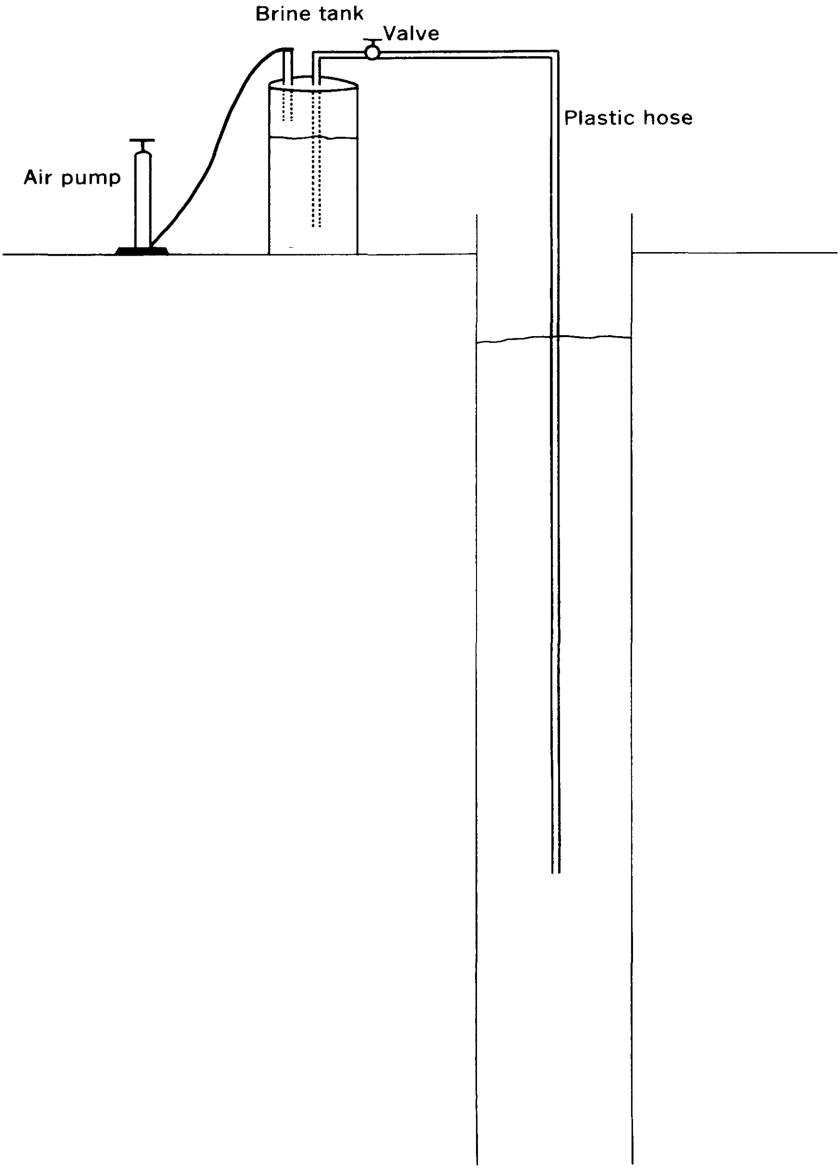

FIGURE 1.—Diagram of brine-injection apparatus.

ability is greatest that an individual fluid particle injected into the conduit will move with this velocity. Therefore, most of the injected brine particles must move with the velocity v_m, and the point of maximum concentration will appear to move with this velocity.

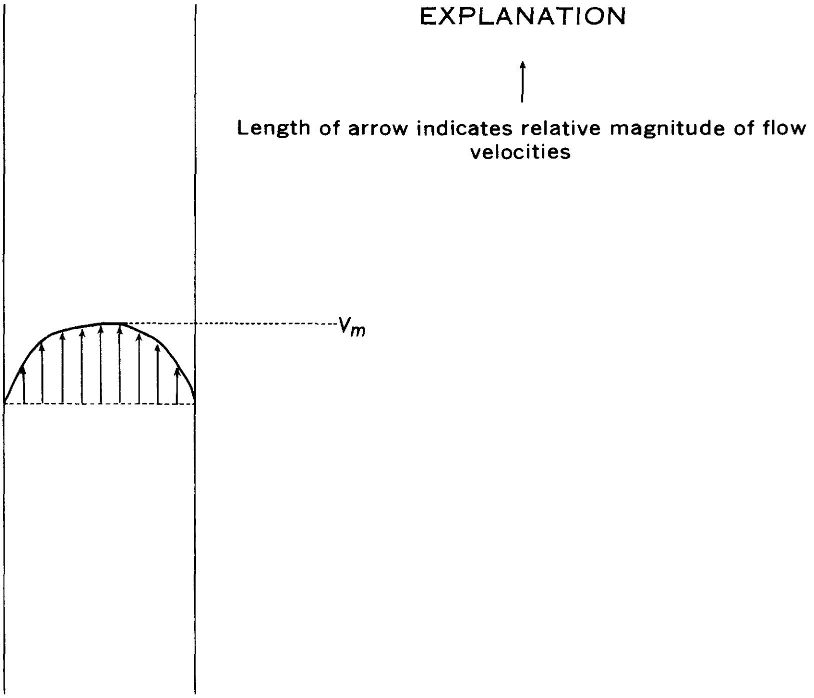

FIGURE 2.—Diagram showing probable form of velocity profile of flow in a well.

In most tests this velocity will be close enough to the average velocity to be used without correction in discharge calculations. In some tests, however, it may be necessary to estimate or empirically evaluate a correction factor. About the only way that such a factor can be evaluated in a well is by injecting brine in the casing, or at least above the uppermost yielding zone, while operating the pump at a known discharge. To determine the necessary correction the velocity obtained by tracing the point of maximum conductivity can be compared with the quantity computed by the following equation.

$$\text{Average velocity (fps)} = \frac{\text{pump discharge (cfs)}}{\text{borehole area (sq ft)}}$$

The correction obtained by this method is actually no more than an estimate, as the flow-velocity profile may have a different form in the casing than elsewhere in the borehole. However, the correction itself will normally be small, and an estimate obtained by this method should be satisfactory in most cases.

Settling of the brine slug due to gravity will usually be a negligible factor. If uncertainty exists on this point, brine can be injected in the casing when no pumping is in progress, and the effects of settling

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can be observed by conductivity tracing. If appreciable settling is observed a correction can be established. It is important to note that this type of control should be established in tightly cased intervals, as flow between aquifers may be present in uncased intervals of the well when pumping is not in progress, and this flow might in some cases be mistaken for settling.

The brine-tracing method is strictly applicable only over intervals in which the flow is constant—that is, in the intervals between points of water entry to the borehole. If the flow is gradually changing due to inflow or outflow through the wall of the borehole, the best result that can be obtained is an average velocity for the zone of measurement. Even this result may be difficult to achieve because the radial inflow or outflow will tend to disrupt the shape of the brine slug. The brine-tracing method is best suited to wells in which the water-yielding zones are separated by wide nonyielding intervals. In such wells the movement of the brine may be traced over relatively long distances, and the errors in measurement of velocity can be held to a minimum.

REPORT OF FIELD TESTS

Field testing of the method consisted of a series of brine-tracing runs made in a well casing 10.2 inches in diameter, as the well was pumped at several different rates. The logging device, or sonde, used was 3 inches in diameter. The tracing interval in this series was never longer than 14 feet, as shown in table 1. Results were good in spite of this relatively short interval, but longer intervals should give correspondingly better results, as errors in distance measurement will be relatively smaller. Figure 3 shows a typical resistivity log obtained in the field tests of the brine-tracing method.

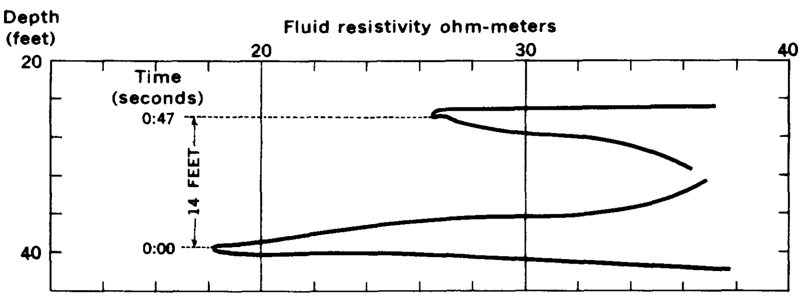

FIGURE 3.—Graph showing resistivity of borehole fluid obtained in measurement of internal flow by brine-tracing method.

TABLE 1.—*Results of brine-tracing field tests*

Distance between deflections (feet)	Time interval between deflections (seconds)	Velocity of point minimum resistivity (feet per minute)	Velocity computed from pumpage (feet per minute)
3. 5	615	0. 34	0. 52
12. 5	419	1. 79	2. 0
13	160	4. 88	5. 2
14	120	7. 00	7. 9
14	92	9. 13	9. 1
13. 5	79	10. 25	11. 0
14. 0	47	17. 87	17. 3
11. 5	30	23. 00	24. 3
11. 5	24	28. 75	31. 1

The measurements were made by the following procedure. The logging sonde, in this case a fluid-resistivity instrument, was suspended below the point of injection. A slug of brine was injected—using the plastic-hose device described previously. The sonde was drawn up through the slug, and a notation was made of the time at which the point of minimum resistivity was passed. The sonde was then drawn up another 10 to 15 feet and held stationary. When the recorder indicated that the point of minimum resistivity had almost reached the sonde's position, the sonde was lowered through the slug, and again a notation was made of the time at which the point of minimum resistivity was passed. The total time of the slug's travel was then obtained by subtracting the two recorded times, and the depth measurement was taken directly from the resistivity log. The prevailing borehole velocity was obtained from these measurements and was then compared with the average velocity, which was determined by dividing the measured pump discharge by the borehole area. The results of several such comparisons are summarized in table 1 and figure 4.

Figure 4 indicates that the errors are random and do not increase or decrease regularly with increasing velocity. The authors believe that the most probable source of error was the distortion of the slug caused by mixing by the measuring device as it moved through the brine slug. The difference in velocities across the well bore, as illustrated by figure 2, apparently had no appreciable effect, because errors due to this effect would be consistently positive and would tend to decrease as velocities increased.

The greatest percentage error occurs at the lowest velocity, for which the distance between resistivity minima was 3.5 feet. The authors believe that the poor results in this case indicate that this interval is too short relative to the disturbances in the position of the slug caused by the motion of the sonde. A positive error due to

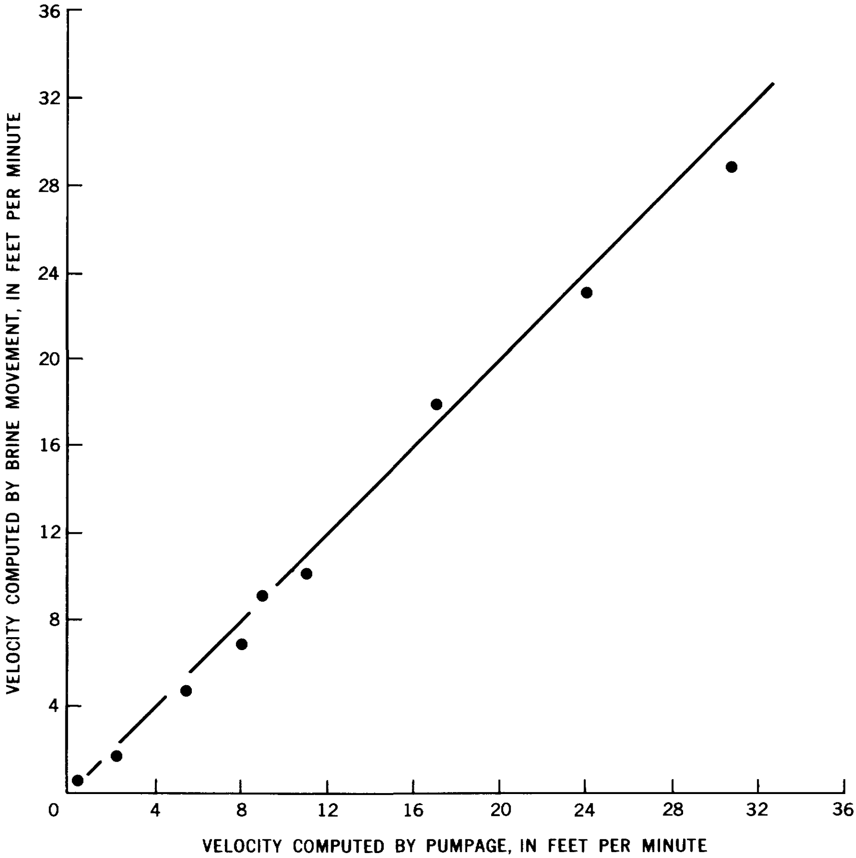

FIGURE 4.—Graph showing comparison of brine-tracing results with average borehole velocities. All measurements made in cased part of one well at different rates of discharge.

the difference in velocities across the borehole probably was in this measurement, but was obscured by the large negative error due to the movement of the probe.

The greatest error in the remaining measurements amounts to about 11.5 percent. The authors believe that much greater accuracy can be achieved when a longer interval of measurement is available, because the errors due to disturbance by the logging sonde will constitute a smaller fraction of the interval. Errors of about 10 percent can be expected when conventional logging equipment and a measuring interval of 10 to 15 feet are used.

SUMMARY

The brine-tracing method involves field procedures which are considerably more troublesome than those involved in the use of flowmeters that consist of a single device in the well. The method cannot be used when the measurements must be made at a precise depth rather than over an interval of borehole; it will not give satisfactory results when used in an interval of borehole in which fluid is entering the well; and it is not suitable in applications which require a number of measurements in rapid succession.

The method has certain advantages, however, that use of the direct-measuring instruments lacks, and it should, therefore, remain an important technique in the foreseeable future. For example, brine tracing requires little instrumental calibration, and errors because of equipment failure or deterioration are uncommon. Also, a high degree of accuracy can probably be achieved when a long interval of borehole is available for measurement. Finally, brine tracing can be relied upon to indicate direction of flow clearly at velocities so low that a flowmeter may not indicate any flow.

Some of the disadvantages of the brine-tracing technique might be eliminated by designing specialized equipment for the purpose. Two fixed conductivity electrodes, suspended at a known separation on a single cable, would be very much superior to the single movable logging sonde as the need for traversing the brine slug with the instrument would be eliminated. An automatic brine release system (incorporated into the same downhole unit as the pickup electrodes) would add greatly to the convenience of the method. Finally, an automatic system in the control unit for recording the time required for the brine to move from one electrode to the other would probably result in greater accuracy and might permit relatively close spacing of the pickup electrodes.

THERMAL FLOWMETER

The thermal flowmeter was developed by H. E. Skibitzke of the Ground Water Branch, U.S. Geological Survey (1955). Several experimental models of the meter were furnished the Harrisburg office of the Ground Water Branch for field testing. Some of the results of these tests are given in the following discussion. Emphasis will be placed upon the performance of the meter itself rather than upon the recording circuit or logging reel, as these components will probably be modified in many respects as the meter comes into general use.

INSTRUMENTATION AND EQUIPMENT

The thermal flowmeter consists of a small brass tube, five-eighths of an inch in diameter and about 6 inches long as shown in figure 5.

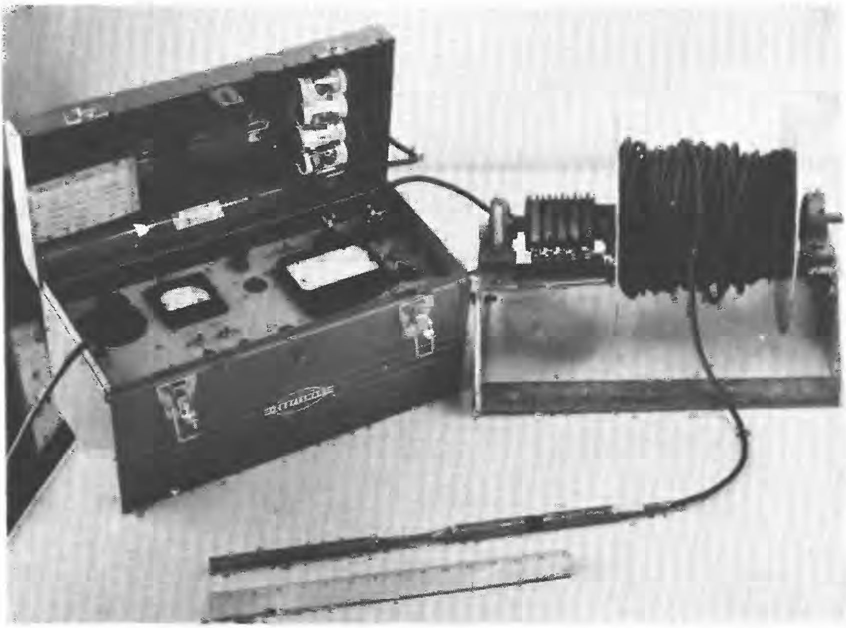

FIGURE 5.—Photograph of thermal flowmeter and related equipment.

Two thermistors and an electrical heating element are arranged as shown in figure 6, which also shows a schematic diagram of the control and recording unit used by the authors. The two wires leading from the heating element are connected to an AC power supply at the surface. The thermistors constitute two branches of a wheatstone bridge circuit, and the other branches of this bridge are variable resistors in the control box.

The tests described here were made with a recording unit in which the galvanometer current of the bridge is fed into a simple amplifying circuit whose output is then recorded as a microammeter deflection. The five-conductor cable, which terminates in special plugs for connection to the flowmeter and control box, was carried on a hand reel. The flowmeters were equipped with centering devices and, when used for low velocities, with devices for channeling flow into the tube. Both these devices are on the flowmeter shown in figure 7. The recording unit and power supply operate on an ordinary 110-volt 60-cycle supply.

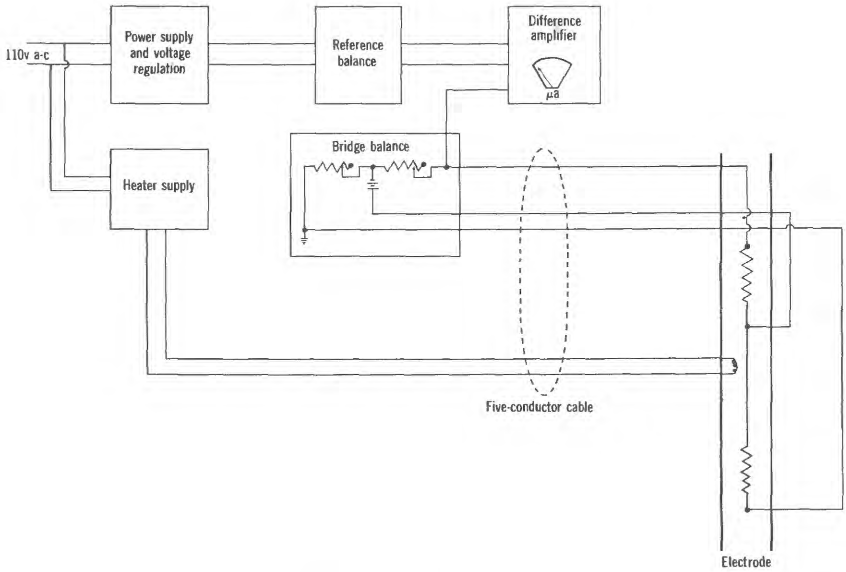

Figure 6.—Schematic diagram of thermal flowmeter tube and electrical components.

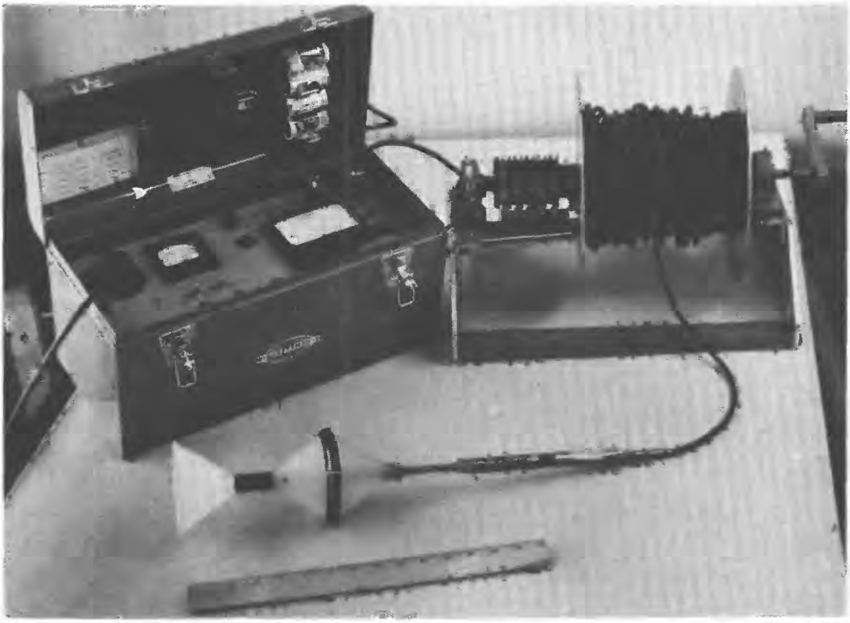

Figure 7.—Photograph of thermal flowmeter equipped with centering and flow-channeling devices.

THEORETICAL CONSIDERATIONS

The operation of the flowmeter depends upon a sequence of effects, through which the flow velocity in the well bore outside the meter is related to the response of the recording unit. The flow velocity outside the meter is related to the velocity through the tube in a manner which will be discussed below. The amount the water is warmed as it passes the heater is an inverse function of the flow velocity. The amount of warming is measured by two thermistors, one of which, upstream from the heater, is approximately at the ambient temperature of the well water; the other, downstream from the heater, is approximately at the temperature of the warmed water. The response of the thermistors is such that a change of temperature causes a change in the electrical resistance, which in turn unbalances the wheatstone bridge and causes a change in the amount of current flowing through the galvanometer and recording circuits. In practice the instrument is calibrated empirically by recording the final galvanometer deflection as a function of known external velocities, thus leapfrogging the various intermediate variables. A brief discussion of the interdependence of these variables, however, may help to explain certain characteristics of the meter's response.

The thermistors in the flowmeter tube possess high negative temperature coefficients of resistance. They show large decreases in resistance as temperature is increased, and large increases in resistance as temperature is decreased. Neither the temperature-resistance curve nor the current-voltage curve of a typical thermistor is linear. The current-voltage curve is nonlinear because a thermistor, like any other resistor, is heated to some degree by the current passing through it. This heating lowers resistance, so that a larger current can pass than might have been predicted by the linear form of Ohm's Law. These relatively complex characteristics make it difficult to predict exactly what the electrical response of the measuring circuit will be to a given temperature difference between flowmeter thermistors.

The relation between the flow velocity within the flowmeter tube and the temperature difference between thermistors has as many complicating factors as the relation between thermistor temperatures and electrical response. When there is no flow through the flowmeter tube, heat is transferred from the heater to the thermistors by conduction through the water and the walls of the tube. The bridge circuit of the meter is generally balanced for this condition of zero flow; any additional transfer of heat will then throw the bridge out of balance, unless this transfer is equal in both directions and the characteristics of the two thermistors are identical. Flow of fluid in the tube creates an additional heat transfer by convection.

The results of the convective process are difficult to predict in view of the many ways in which it can affect the device. The process increases the rate of heat transfer in the direction of flow and decreases it in the opposite direction, thus tending to bring the temperature of the upstream thermistor to the temperature of the well water. At the same time, the flow cuts down the ability of the heater to increase the temperature of the surrounding water and interferes with conduction through the walls of the tube by providing greater opportunity for heat loss from the walls to the water passing through. It is clear, therefore, that the difference in thermistor temperatures will not generally be a linear function of the flow velocity within the tube.

The velocity within the flowmeter tube is, of course, quite different from the velocity outside the tube. For velocities above 10 fpm (feet per minute) the meter is generally used without a flow-channeling device and acts somewhat in the manner of a Pitot tube, as shown in figure 8. The velocity along the streamline A–B falls rapidly toward zero as point B is approached, so that an increase in head of $\frac{v^2}{2g}$ (where v is the fluid velocity that existed at point B prior to insertion of the flowmeter, and g is the gravitational constant) occurs at the lower end of the tube. A decrease in head, $-h_t$, occurs at the upper end of the tube owing to turbulence. The flow velocity through the tube depends upon the head differential, $\frac{v^2}{2g}-h_t$, and upon the frictional resistance of the tube. Thus the flow velocity within the tube is much smaller than the velocity in the well. When the meter is used in this way, it measures the velocity at a particular point in the cross section of the well. If the velocity profile has the form illustrated in figure 2, a simple centering device will insure that the quantity measured is v_m, the velocity in the central part of the well bore.

For velocities lower than 10 fpm the meter does not usually respond well when used as shown in figure 8. The authors were able to obtain useful results in this velocity range, however, by attaching a funnel-shaped, flow-channeling device to the end of the tube. A sizeable fraction of the well flow is thus diverted through the flowmeter tube. When used in this manner, the velocity through the flowmeter is no longer directly dependent on the velocity in the well, as the response of the meter will be affected by the percentage of the total well flow that is diverted through it by the channeling device. This percentage will, of course, vary as the ratio of the cross-sectional areas of the well and the flow-channeling device. Therefore, the meter must be calibrated separately for each well diameter that may be encoun-

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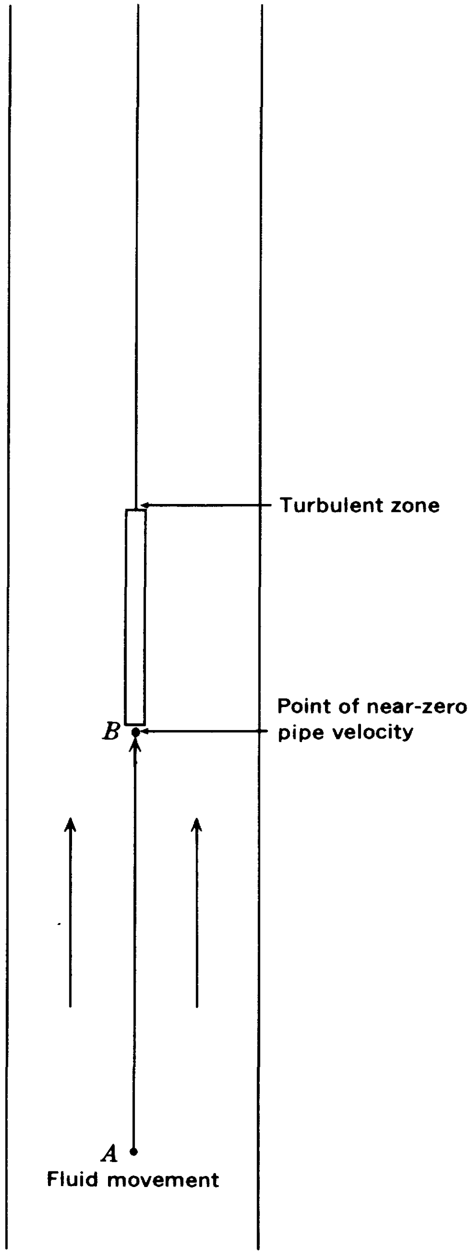

FIGURE 8.—Diagram of thermal flowmeter as used without flow-channeling device, showing Pitot effect.

tered by relating total discharge past the meter to the response of the device.

This discussion of the variables through which flow velocity is related to meter response should illustrate that the response will not be a linear function of the velocity. In general, rather, the velocity-response curve will be difficult to describe mathematically. This, of course, has no bearing upon the utility of the instrument, as the only requirements are that a certain response correspond to a certain flow velocity within the well bore and that empirical methods can establish the necessary correlation.

Differences in water temperature in the range normally found in ground-water work have no measurable effect upon the operation of the meter. Since the thermistors constitute two arms of a bridge circuit, the response of the device is controlled by the difference in their temperatures rather than by the absolute magnitude of these temperatures. The downstream thermistor adjusts approximately to the temperature of the well water, and the difference between this temperature and that of the upstream thermistor is governed by the heat-transfer processes described previously.

CALIBRATION AND RELIABILITY

Figures 9 and 10 show typical calibration curves for the thermal flowmeter. Each figure shows two curves, corresponding to constant heater currents of different magnitudes. Figure 9 shows the response of a meter used as diagrammed in figure 8. The tests from which these curves were constructed were made in the laboratory and cover a relatively wide velocity range. The meter was highly unstable at velocities lower than 10 fpm.

Figure 10 shows the response of another meter which was tested in the field and was equipped with the simple flow-channeling device. The curves are scaled in terms of average velocity and apply only for the well size in question; the data was taken by suspending the meter in a casing 13 inches in diameter and pumping at several different rates. The curves indicate that this device will give reliable results for average flow velocities as low as 2 fpm.

Each calibration curve represents the most reasonable, smoothest fit that could be made to the experimental data. The accuracy and reliability that can be expected from the device may be estimated from the relation between the slope of the calibration curve and the accuracy with which the recording meter can be read.

The possible error in reading the meter on the recording unit used by the authors was ± 1 microampere. Figures 9 and 10 indicate that by proper selection of the heat input it is possible to obtain a curve having

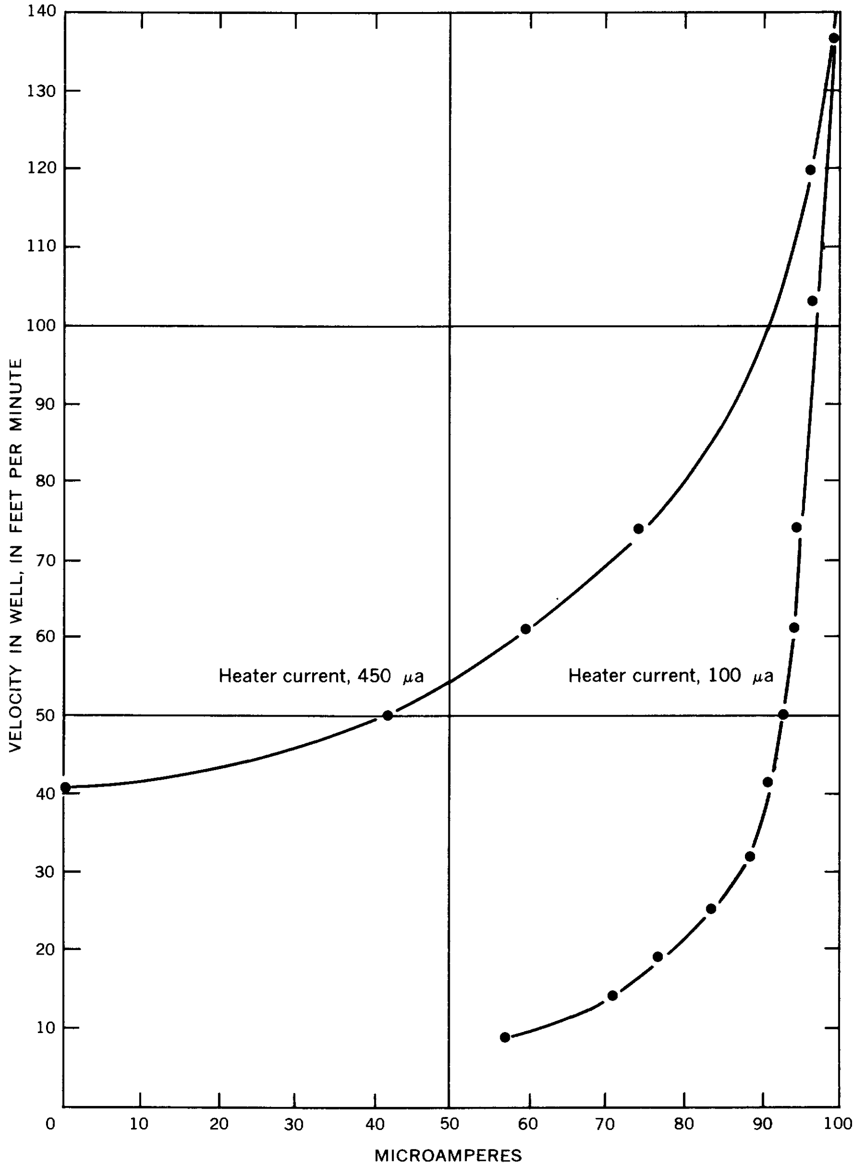

FIGURE 9.—Typical calibration curves for thermal flowmeter used without flow-channeling device.

a slope of less than 1 fpm per microampere for any velocity interval between 2 and 75 fpm. At the lower velocities, slopes of less than 0.5 fpm per microampere were obtained. Errors greater than ±1 fpm

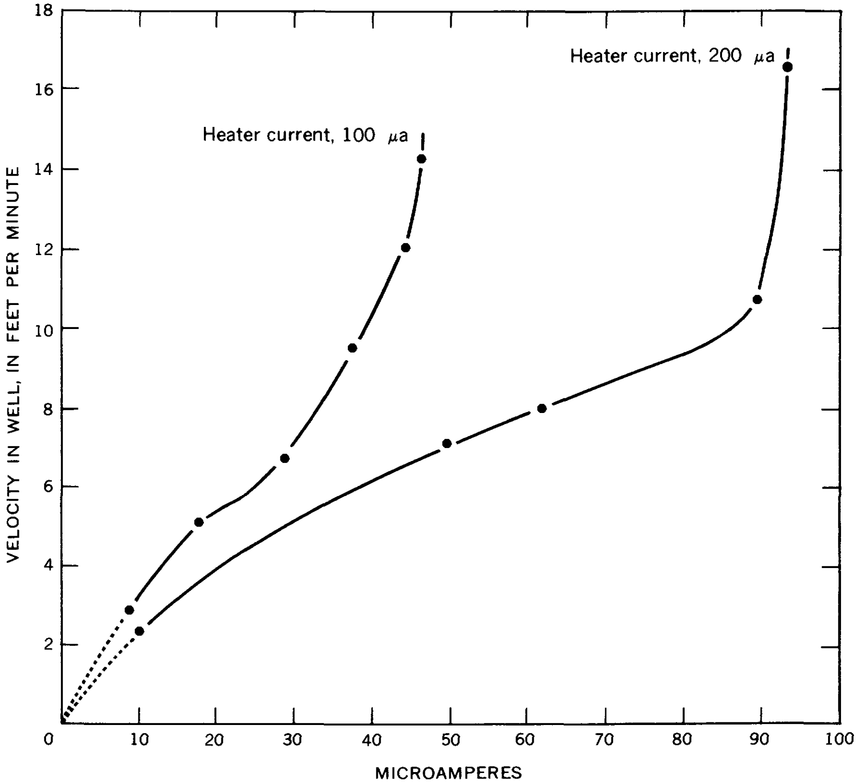

FIGURE 10.—Typical calibration curves for thermal flowmeter used with flow-channeling device.

are, therefore, unlikely at the higher velocities, and errors greater than 0.5 fpm are unlikely at the lower velocities.

The devices tested by the authors showed a flattening of the calibration curves at velocities above 75 fpm and a corresponding reduction in accuracy. It would be possible to construct probes to give accurate results in this velocity range. Flow velocities in a borehole are not generally that high, however, and the meters tested by the authors seemed adequate to handle most situations that are likely to be encountered in the field.

It should be noted that separate calibration curves must be run for downward flow, because the cable and connections extending upward from the meter may obstruct the flow into the upper end of the tube. In general, some sort of flow-channeling device attached to the upper end of the tube is necessary for reliable measurement of downward discharges, and the calibration must, therefore, be in terms of discharge for the well size in question. The design of the meter is such that the galvanometer current of the bridge circuit will be reversed as the flow is reversed, so that any recording system based upon direct amplification of this current will indicate flow direction by a positive or a negative response.

SUMMARY

The thermal flowmeter method seems to be the most promising method of borehole flow measurement currently in use. Although the instruments tested by the authors were experimental models, good results were achieved both in the laboratory and in the field. It was found that by adjusting the heat input to obtain a favorable calibration curve for the velocity interval in question, and by using a flow-channeling device for the lower velocities, reasonably accurate measurements could be made over a very wide range.

The small size of the probe represents an advantage over most other instruments of measurement, in that the necessity for lowering bulky metering or tracing equipment in the well is eliminated, and the danger of fouling is thus greatly reduced. Measurements generally can be made much more rapidly than by any of the other methods; however, a minute or so may be required for the thermistors to reach equilibrium after a large change in flow has occurred, and because of this the authors found that measurement with the meter in a fixed position was preferable to continuous logging.

In accuracy and range of reliable measurement, the thermal flowmeter method tested by the authors was comparable to the other methods tested. The meters tested were experimental models, and future improvements in the meters will probably result in improved accuracy and reliability. The thermal flowmeter method is the most convenient method of measurement tested, and it appears to be the method best suited for incorporation into a well-logging unit. Of the three methods tested, therefore, it seems to hold the best prospects for the future.

AU DEEP-WELL CURRENT METER

The U.S. Geological Survey has used the Au deep-well current meter for borehole flow measurement for a number of years. This meter was designed by C. H. Au of the Geological Survey and was described by Fiedler (1927). It is described here chiefly for the sake of comparison with other methods.

INSTRUMENTATION, EQUIPMENT, AND THEORY

The meter consists of a roughly helical turbine, or rotor, mounted on a vertical axis in a metal cylinder, as shown in figure 11. The axis of the rotor coincides with that of the cylinder, and is mounted

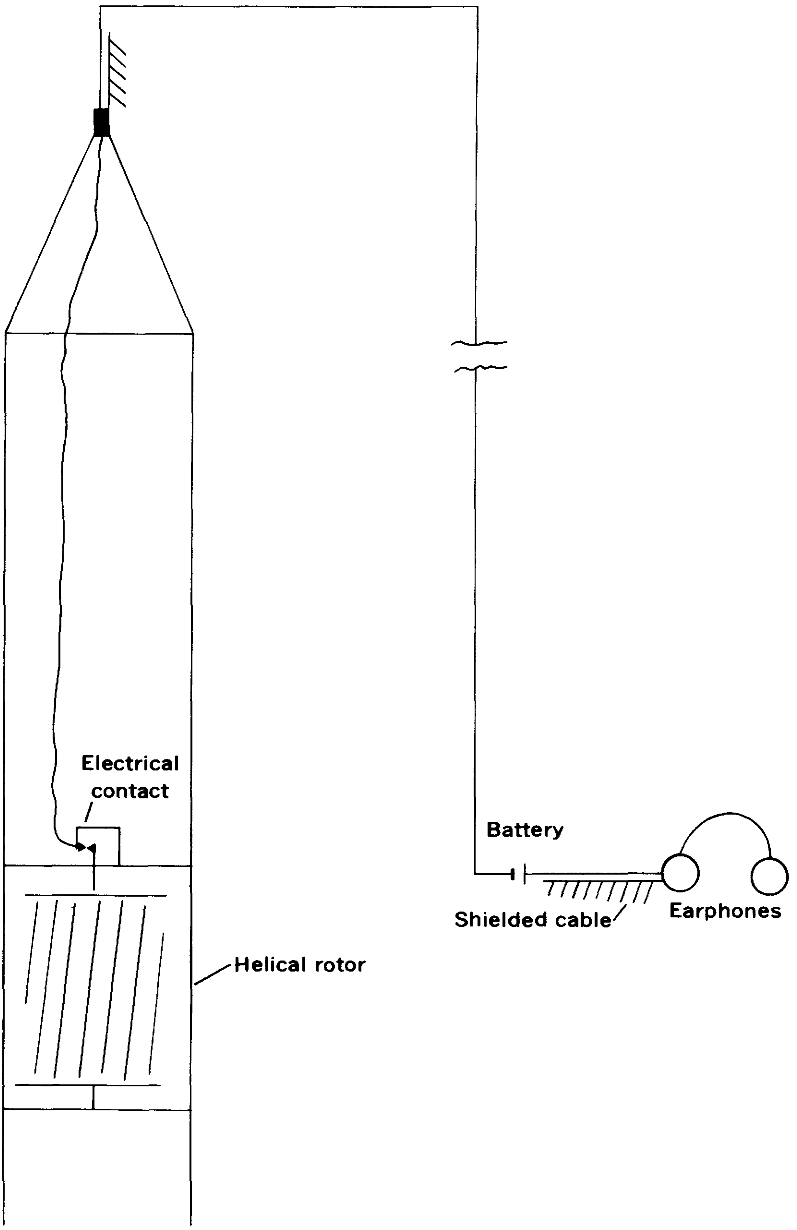

FIGURE 11.—Schematic diagram of Au deep-well current meter and recording circuit.

between supports extending from the cylinder wall. The interior of the cylinder is unobstructed except for the rotor, rotor supports, and electrical contacts.

The meter is suspended on a two-conductor electrical cable. One conductor is connected to the cylinder wall and, thus, to the metal axis of the rotor; the other is separated from the body of the meter by an insulating support and terminates in a light, flexible strip of metal extending toward the axis. With each revolution of the rotor, a slight protrusion on the axis makes contact briefly with the metal strip. The cable is actually part of a simple electrical circuit which includes, at the surface, a battery and a pair of earphones, as shown in figure 11. Thus, with each revolution of the blade the circuit is closed for an instant, and a click is heard in the earphones. A record of the number of clicks heard in a given time interval indicates the number of revolutions that occurred in that interval.

The relation between fluid velocity and the rate of rotation of the turbine blade is difficult to analyze theoretically. It depends upon the design and inertia of the blade, the friction in the bearings, and the relation between the total flow through the well bore and the flow through the cylindrical turbine housing. In general, increases in the velocity of flow in the well produce increases in the rate of revolution of the turbine blade, but the response is not necessarily linear. The relation between velocity and meter response is determined by empirical calibration. A centering device attached to the meter insures that the meter response is a measure of the prevailing velocity, v_m (fig. 2).

The meter tested by the authors shown in figure 12 was equipped with flexible rubber flow guides designed to channel maximum flow into the turbine housing. Thus equipped, the meter must be calibrated in terms of volumetric discharge, or average borehole velocity, for each well diameter in which it is to be used.

CALIBRATION AND RELIABILITY

A calibration curve for the meter tested by the authors is shown in figure 13. The curve shows the performance of the meter for flows of 2 to 8 fpm in a casing 13 inches in diameter. It represents the most reasonable fit that could be made to plots of the experimental data. The maximum deviation of plotted measurements from the curve is approximately 0.2 fpm, which indicates that errors greater than 3 or 4 percent are not likely in the use of this meter in a 13-inch well. This is true, of course, only if the flow velocity in the borehole is in the ranges covered by figure 13, the instrument is centered in the well as it was during calibration, and the measurements of revolutions per minute are at least as accurate as those made during calibration.

In obtaining the data for figure 13 the time necessary for 30 revolutions was measured by a stopwatch. The watch was started at a click,

FIGURE 12.—Photograph of Au deep-well current meter equipped with rubber flow guides. Reel, cable, and accessory equipment are shown.

and stopped at the 30th following click. The time intervals involved were more than 1 minute in all cases, and random errors in time measurement should, therefore, be quite small. If the meter is used where

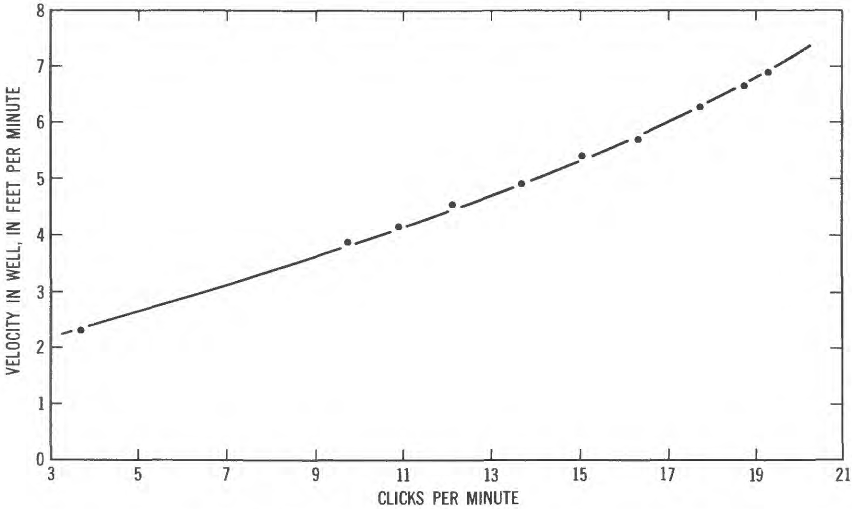

FIGURE 13.—Calibration curve for Au deep-well current meter.

rapid measurements of discharge are required, the time interval available for each measurement may be considerably less than 1 minute, and the reliability of the measurements will be lessened correspondingly.

The meter tested by the authors gave no response to flows of less than 2 fpm. This fact illustrates a defect common to all turbine-type meters; there is always a limiting velocity below which the rotor will not turn. This limit should always be determined during calibration. There are various factors which will cause a meter of this type to have an upper limiting velocity above which the device fails to indicate further increases in flow reliably. In general, however, the flow velocities in wells are relatively low, and the upper operating limit of a meter is seldom exceeded in the field.

It should be noted that because of the cable and supports above the rotor, and because of the presence of packers or flow deflectors in some instruments, calibration may be different for downward flow than for upward flow. If possible, therefore, calibration curves for downward flow should be constructed by suspending the meter in a well casing, beneath the water level, and pumping water into the well. During flow measurement in the field, direction can be determined by raising or lowering the meter. If the revolutions per minute of the rotor decreases as the instrument is raised, the flow is upward; if they increase as the meter is raised, the flow is downward. When the direction of flow is known, the velocity can be determined by holding the meter in a fixed position and consulting the proper calibration curve.

SUMMARY

The Au meter is probably the most widely used flowmeter in the U.S. Geological Survey. With suitable centering and flow-channeling equipment it gives good results for discharge measurements in which the average flow velocity within the well bore exceeds 2 fpm. Its simplicity of design minimizes equipment failure in the field and contributes greatly to the reliability of the instrument.

The Au meter is unsatisfactory, however, for the measurement of slow flows and in applications which require a rapid series of flow measurements. Also, it is generally impossible to log continuously with the device, as each measurement must be made with the meter in a fixed position. Despite these disadvantages the Au meter remains one of the best available methods of borehole flow measurement available.

REVIEW OF OTHER METHODS OF FLOW MEASUREMENT

FLOWMETERS IN USE IN THE OIL INDUSTRY

Various turbine-type meters, generally more complex than the Au meter, have been used by the oil industry. The basic principle is the same—some sort of rotor is driven by moving water at an angular rate which is proportional to the flow velocity within the well bore—but refinements have been introduced in the methods of recording, in the design of the housing, and in other respects. Rumble and others (1959) describe a turbine-type meter that records by making and breaking an electric circuit three times during each revolution of the rotor. The device indicates the direction of flow as well as the rate, as the circuit actuators are unevenly spaced, and different pulse sequences are obtained for different directions of rotor revolution. An inflatable packer serves to center the instrument and to force all flow through the turbine chamber. Dale (1949) describes a turbine instrument in which the revolutions of the rotor are recorded through an optical-electrical system as a series of dashes on a moving film. The instrument may be equipped with flow guides of various diameters to center it, as well as to channel flow into the rotor housing. The helical rotor is extremely light in weight, and will respond to the flow of both gases and liquids.

A thermistor flowmeter has been described by Morgan and others (1948). The measurement of flow is made by a single thermistor which is heated by an electric current. This current is held nearly constant. Moving liquid or gas cools the thermistor and causes a change in resistance, which results in a change in the voltage required to maintain the heating current at a constant level. These voltage changes are recorded and indicate the flow rate. The instrument contains a second thermistor, in an essentially separate circuit, which is used to measure fluid temperature. The meter has been used successfully in the measurement of gas flow.

Vincent and others (1948) described a meter that utilizes a hot-wire anemometer as the flow-detecting element. The anemometer constitutes one branch of a wheatstone bridge circuit. A second branch of the bridge is placed in the flow stream to compensate for temperature variations in the well fluid. The bridge circuit permits accurate measurement of the resistance of the hot wire, which varies owing to the cooling effect of the moving fluid, and the change in resistance provides a means of measuring the fluid flow. The authors report the use of the device in determining the producing ability of gas sands.

Piety and Wiley (1952) described another instrument that utilizes the hot-wire principle. The meter consists of a cylinder divided into two coaxial flow tubes. A packer extends from the exterior of this cylinder to the borehole wall, so that all fluid moving in the borehole must pass through one of the two flow tubes. The interior tube contains a small pump, and the outer tube contains the hot-wire element. The pump is controlled from the surface and is calibrated in terms of rotational speed versus fluid discharge. Continuity requires that when the pump is operating at the particular discharge that exists in the well bore, no flow will pass through the outer tube. Cooling of the hot wire will obviously be at a minimum in this condition. Flow measurements are made by adjusting the pump speed until an indicator shows that the hot-wire temperature has reached a maximum. Then, the borehole flow is equal to the calibrated output of the pump. At lower pump speeds a part of the borehole flow passes through the outer tube, and at higher pump speeds a fraction of the pump output recirculates through this tube. Under either of the latter two conditions there will be cooling of the hot-wire element. The meter has been used successfully for water injectivity profiling.

Bardeen and Teplitz (1956) described a meter that responds to the pressure differential between the interior and exterior of a tube that has wide flow-inlet openings but a restricted outlet opening. The pressure differential causes a proportional deflection in a diaphragm in the wall of the tube. This deflection is recorded electrically by placing a potential electrode on the diaphragm and recording voltage differences as the position of this electrode varies between two fixed current electrodes. The instrument is designed to detect zones of lost mud circulation; the inlet openings are at the upper end of the cylinder.

RADIOACTIVE-TRACER METHODS

Radioactive tracers have been used in the oil industry for flow measurements within the well bore and could easily be used in water wells for the same purpose. Bird and Dempsey (1955) reported two methods of measuring flow by using beads of a plastic material in which a radioactive isotope has been dissolved. One method is exactly analogous to the brine-tracing technique, except that a group of these radioactive particles is released in place of the brine slug, and a radioactivity-logging device is used in place of the conductivity-logging device.

The second method, used in the water-injection wells of secondary recovery projects, makes use of the fact that as water containing these radioactive particles enters a porous medium, the particles are filtered out on the face of the medium. A container of the particles is broken in the well during the flooding process, and the relative number of particles that filter out on the face of each sand zone is proportional to the fraction of the well input that is entering that zone. A radioactivity log run shortly after the slug injection indicates the relative amounts of the tracer that have filtered out at each zone.

CONCENTRATION-TIME METHODS

Barbagelata (1928) described a method of flow measurement involving the use of injected brine, which has yielded excellent results in application to channel flow. A variation of this method might be used in a well where certain difficult measurement problems exist. For example, if velocities are too low for detection with any type of flowmeter, and if the depth interval of measurement is too short for safe application of the brine-tracing procedure, the method may prove useful.

The method depends upon the equation

$$N = Q \int_{t_1}^{t_2} C(t)dt \qquad (1)$$

in which N is the total number of particles of a certain type injected into a flow, Q is the fluid discharge (volume/time), $C(t)$ is the concentration of the injected particles (particles/volume) at a given instant at the point of measurement, and t is time. $C(t)$ is a function of time and is considered constant across the flow cross section at the point of measurement; and t_1 and t_2 are two times chosen so that all the injected particles pass the point of measurement between t_1 and t_2, Q is considered constant during the interval $(t_1 - t_2)$. The equation sums the products

$$Q \times \Delta t \times C(t)$$

each of which gives the number of particles that have passed the point of measurement during the interval Δt.

The application of equation 1 to the measurement of flow requires first, knowledge of the total number of injected particles; second, a determination of $C(t)$ in sufficient detail to permit evaluation of the integral, and finally, some method of insuring that the concentration at a given instant is uniform across the flow area at the point of measurement.

In the technique under discussion, a salt solution of some sort is injected into the interval of measurement. It is convenient, in this case, to consider the injected quantity of brine as divided into small units of volume—for example, cubic millimeters—each of which constitutes a particle of the sort referred to in the preceding paragraphs. Concentration of injected particles may then be expressed in terms of cubic millimeters of brine per gallon of borehole fluid. If the equipment described on page C–3 for the brine-tracing method is used, measurement of the quantity of brine in the reservoir before and after injection provides a simple method of determining the injected quantity. A uniform concentration of brine across the borehole area might be obtained by using an injection hose which is perforated radially over an interval of several feet. The greatest difficulty occurs in determining $C(t)$ by use of fluid-conductivity data.

The fluid-conductivity electrode is held in a stationary position downstream from the interval of injection. The electrode and injection device should both lie in an interval from which it is reasonably certain that no water is leaving the borehole. As the brine is carried past the electrode, a record of conductivity as a function of time is made. This record must be converted into a record of concentration as a function of time by a previously established relation between conductivity and concentration.

It is difficult to theorize the nature of this relation between conductivity and the concentration of injected brine, other than to say that an increase in concentration will produce an increase in conductivity The main reason for this vagueness lies in the fact that the sodium-chloride solution is injected into water which generally contains some unknown original concentration of this salt, together with various unknown concentrations of other salts. Under these conditions it is impossible to make a precise theoretical prediction as to how the injected solution will affect the conductivity as very little quantitative data are available on the total conductivity of mixtures of electrolytes.

While the conductivity of individual electrolytes may be known, the total conductivity of a mixture of these electrolytes cannot be predicted because of the complex interaction between ions. In cases where sodium chloride is the only salt present in appreciable quantity, a linear relationship between conductivity and concentration can be applied for a wide range of concentrations; however, the assumption that sodium chloride is the only important solute is usually not justified in dealing with ground water. Thus, an empirical relation between conductivity and the concentration of injected brine must be established. This empirical relation may be obtained in the laboratory if it is possible to obtain a water sample from the depth interval in which the measurement of flow within the well is to be made. A graph showing conductivity versus concentration of injected brine can be constructed, and it can be used to convert the field conductivity readings to brine concentrations.

A graphical evaluation of the integral in equation 1 is the most convenient solution. After the conductivity data has been converted to brine concentration, a plot of concentration versus time is prepared for the interval t_1 to t_2. The area under this graph is measured to give the value of the integral, and equation 1 may then be solved for Q.

The injected-brine method is, of course, troublesome. The development of more elaborate equipment specifically designed for this method might possibly increase the ease and efficiency of field operations, but at present both the operational difficulties and the possible sources of error are numerous. Using the equipment described in the discussion of brine tracing, the authors were unable to obtain acceptable results from the method; this failure may have been due to errors in the relation used to convert conductivities to brine concentrations. The method is included in this discussion because it is felt that it can be made to work, if experimental techniques are improved, and because there are a few measurement problems for which no other method seems adequate.

A radioactive-tracer method similar to the brine-dilution method of Barbagelata has been used in pipe-flow measurement (Hull, 1955). In this method a slug of tracer is substituted for the brine slug, and a counter is substituted for the conductivity bridge. The method might be adapted for well-bore measurements, using radioactivity-logging equipment, and could conceivably avoid certain of the disadvantages of the brine-dilution method.

The use of radioactive tracers in this connection emphasizes the generality of equation 1 and the methods based upon it. It is not necessary to use brine in measuring flow by this technique, as any substance which can be injected easily, and whose concentration can be measured by an instrument suspended in the well, should be satisfactory. It may, in fact, be worthwhile to seek some injection substance whose detection is unaffected by natural substances in the well. The conductivity measurement, as indicated above, is affected by ions present naturally in the well water; a radioactivity measurement, in the same way, might be affected by the natural radioactivity of the wall rock. Difficulties of this sort would be avoided in a system in which the measuring device could respond only to injected material.

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