A Thermal Flowmeter for Measuring Velocity of Flow in a Well

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A THERMAL FLOWMETER FOR MEASURING VELOCITY OF FLOW IN A WELL

By Howard T. Chapman and Albert E. Robinson

ABSTRACT

A small flowmeter for measuring the rate of vertical flow in a well has been developed by the U.S. Geological Survey. The flowmeter is based on the principle of heating the water with an electrical heater and measuring the temperature difference between a point below and a point above the heater. The development, construction, and operation of the meter are described. The meter gives accurate results when measuring velocities of 1 to 20 feet per minute.

INTRODUCTION

Data on vertical flow in wells are important because they can be used to determine the permeability of an aquifer. Measurements of the rates of vertical flow at different depths in a pumped well reveal the location, thickness, and relative productivity of water-bearing zones. Similar information can be obtained if vertical flow occurs in a well not being pumped. Such measurements in the past have rarely been feasible because of the lack of a meter suitable for most field conditions.

The two principal requirements in constructing a satisfactory flowmeter are as follows: (1) the sensing unit must be small enough to be lowered into the well past the pump bowls through openings whose annular clearances may be less than an inch, and (2) the flowmeter must be capable of measuring low velocities, on the order of 20 fpm (feet per minute) or less. Existing mechanical flowmeters are too large to bypass the pump installations and are not suitable for measuring velocities as low as those normally found in an unpumped well. The U.S. Geological Survey has attempted to develop small mechanical flowmeters, but such small instruments are generally unsatisfactory in the field because they are delicate and may be disabled by a single grain of sand.

A consideration of nonmechanical flowmeters led to the idea of using a combination of an electrical heater as a heat source and thermistors to make up a sensing unit. A thermistor is an electrical resistor whose resistance changes at a known rate with changes in temperature. On March 12, 1953, the U.S. Geological Survey filed for a patent on such a device, called a Thermal Flowmeter. The patent, No. 2,728,225, is dated December 27, 1955. The pilot model described in the patent consists of an electric heater installed in a tube. When a fluid passes through the tube, it is heated and then flows past a thermistor. A change in the temperature of the fluid causes the resistance of the thermistor to change also and alter the amount of current flowing through it. The amount the temperature of the water rises depends on the rate of flow past the heater, and on the amount of heat being emitted by the heater. The fluctuation of electrical current caused by changes in resistance due to the heating of the water is measured by a meter at the ground surface. A velocity-rating curve can be produced by plotting a graph of the current readings for a range of known velocities. An unknown velocity can then be measured indirectly by utilizing this rating curve.

Because the temperature of the water in a well may vary with depth, or with time during pumping, it is evident that something must be done to compensate for the effect of such changes on the thermistor. This problem is solved by placing a second thermistor ahead of the heater. The two thermistors are wired in the form of two legs of a bridge circuit, and the signal received at the electronic meter becomes that of the electrical current owing to the unbalanced resistance between the two thermistors. Thus, the signal is proportional to the product of the difference in resistance between the two thermistors, regardless of the temperature of the surrounding water.

The range of velocities that can be measured accurately depends on the amount of heat generated by the heater, and on the throat diameter of the tube lining the inside of the heating element. The experimental unit was able to give consistent velocity readings with changes in water temperature.

The experimental sensing unit described in this report was designed to measure low velocities, ranging from 1 to 20 fpm. This prototype may not be of the best design attainable, but it is compact and reliable. Velocities of more than 100 fpm have been measured by other experimental thermal sensing units designed with larger liner tubes through the heater sections than the one described here, and containing baffles to stir and mix the heated water. Although development of a current meter to measure vertical velocities larger than 20 fpm could be useful too, the particular pilot model referred to in this report and most of the other experimental models used in this investigation were designed for measuring low velocities only.

DESIGN OF FLOWMETER

SENSING UNIT

The sensing unit consists of a heating element, two thermistors, a brass body through which the water flows, and an outside housing (fig. 1). The body of the sensing unit is a 3/16-inch ID brass tube 3.50 inches long joined to two 1.875-inch lengths of 1/2-inch OD brass tubing. The total length of the sensing unit is 7.25 inches. The electric heating element is wound around the smaller brass tube. The outside of the heating element is coated with an insulating material to a diameter of half an inch. A thermistor is placed in each 1/2-inch tube, 0.650 inch from the ends of the narrower central tube which lines the heating element.

The body of the sensing unit, including the thermistors and the heating element, is inserted into the outside housing, a 5/8-inch OD brass tube. (See fig. 1.) The ends are soldered to seal the electrical components. To prevent water leakage where the thermistors protrude, a sealer composed of 100 parts by weight of Furane's No. 202 epoxy resin and 10 parts by weight of Furane's No. 951 Hardener fills the annular opening between the 1/2-inch tube and the 5/8-inch housing. A flattened tube houses the wires that leave the sensing unit; this tube also is filled with the same epoxy compound.

The upper thermistor is a "Veco" No. 32A1D8, which is 2 inches long; the lower is a "Veco" No. 32A11–N8, which is 1/2 inch long. These are nominal lengths and are trimmed to fit in their respective positions. In spite of their different lengths, their electrical characteristics are identical. The nominal resistance of each thermistor is 2,000 (±20 percent) ohms at 25° C. The two wires from the heating element, at points *a* and *a′* on figure 1, and the two leads from the bottom thermistor, at point *b*, are brought to the upper end of the sensing unit as shown in figure 1. The wires enter the body of the sensing unit through two holes near its top, at points *c* and *d*. The upper end of the body of the sensing tube is soldered to a 5/16-inch OD brass tube that has been flattened and forms a housing for all wires leaving the sensing unit. The flattened tube is soldered to the body in such a manner that it covers the wire openings but still allows the water to pass. This part of the unit is shown as section *X–X′* at the bottom of figure 1.

The maximum capacity of the heating element in the sensing unit is 100 watts in air. By setting the dial of a variable transformer, or

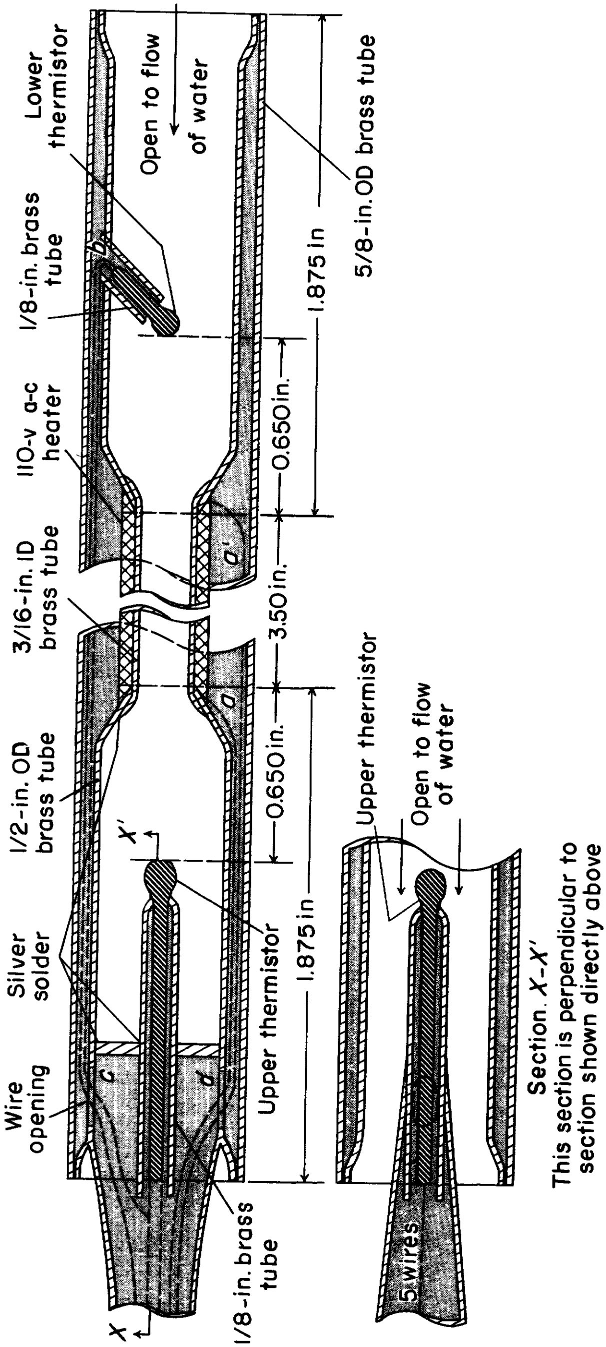


FIGURE 1.—Sections of the thermal sensing unit. Shaded areas represent epoxy-filled spaces to prevent water leakage. Overall length 7.25 inches.

Variac (General Radio Corp., Type 200B), on the instrument panel, the output of the heating element can be positively and accurately controlled from 0 to 100 watts. The output amperage is read on an a-c ammeter in series with the output of the Variac to the heating element. The heating element described in this report uses 0.15 ampere.

The two thermistors form two legs of a bridge circuit. One wire is common to both thermistors, and only 3 wires are needed for the circuitry of the 2 thermistors. In addition to the 3 wires for the 2 thermistors, 2 wires are required for the heating element. In the laboratory a 5-conductor cable, Belden 8455, was used, which provided 2 No. 18 and 3 No. 22 stranded wires. The 2 No. 18 wires are connected to the heating element and the 3 No. 22 wires are used for the thermistors. Belden 8455 cable comes in standard 250-foot lengths; longer lengths are available on special order from the manufacturer.

A manufacturer has been contacted to produce a 5-prong quick connector for attaching the thermal sensing unit to the 5-wire cable. A connector could be made that would be watertight and sufficiently small (5/8-inch diameter) to allow the sensing unit to pass through small openings.

Figure 2 shows a generalized diagrammatic view of the electrical circuit of the thermal sensing unit and its relation to the bridge circuit; figure 3 shows a detailed wiring diagram for the entire flowmeter and bridge unit. In the absence of heat from the heating element and with water passing through the unit, both thermistors are at the same temperature and the bridge can be balanced with 100-ohm bridge balance potentiometer. When heat is applied the signal thermistor is heated, and its resistance decreases so that more current will flow through this leg of the bridge. It is this current change, caused by the unbalancing of the bridge circuit, that is the signal to the differential amplifier and that is measured. The current changes are related in the laboratory to controlled velocities of water flowing through the meter, and a rating curve similar to that shown in figure 4 is developed. The rating curve shows the relation of changes in electrical current to changes in water velocity. Velocities in wells are then determined by using the rating curve.

CONTROL UNIT

The electronic controls (Variac and amplifier) of the thermal flowmeter are mounted on an 8- by 9½-inch panel. The makeup of the electronic control circuit is shown in detail in figure 3, and figure 5 shows the front of the instrument panel with the controls and their location. The panel is set in an 8½- by 8- by 20-inch toolbox. The

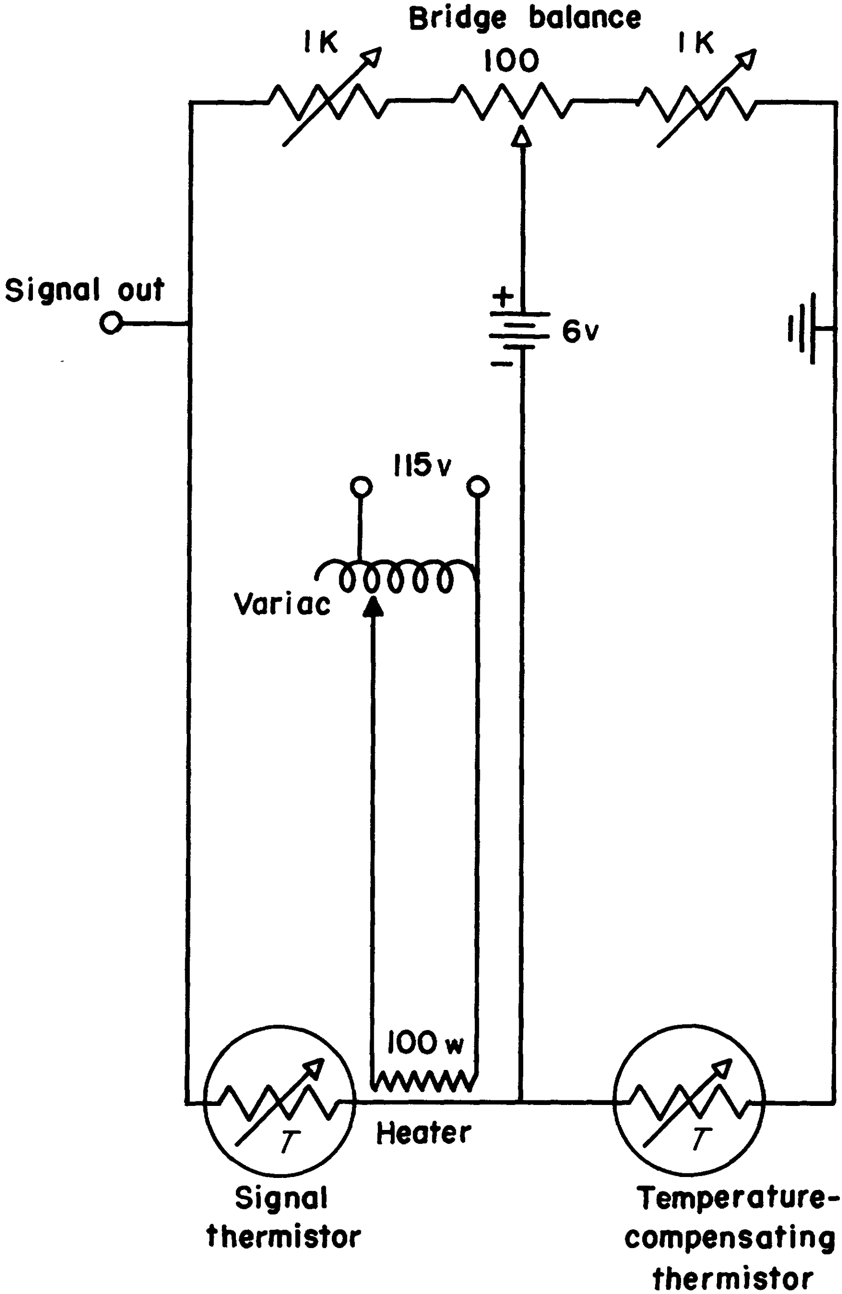


FIGURE 2.—Generalized wiring diagram of thermal flowmeter.

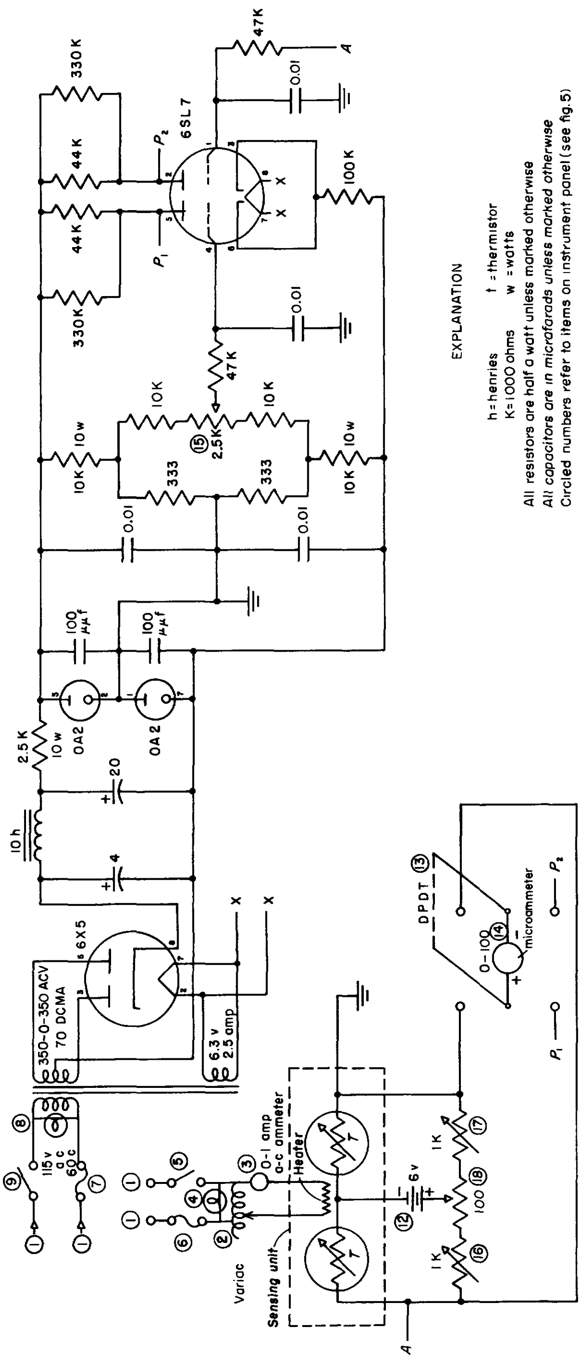


FIGURE 3.—Detailed wiring diagram of thermal flowmeter. (U.S. Pat. 2728225)

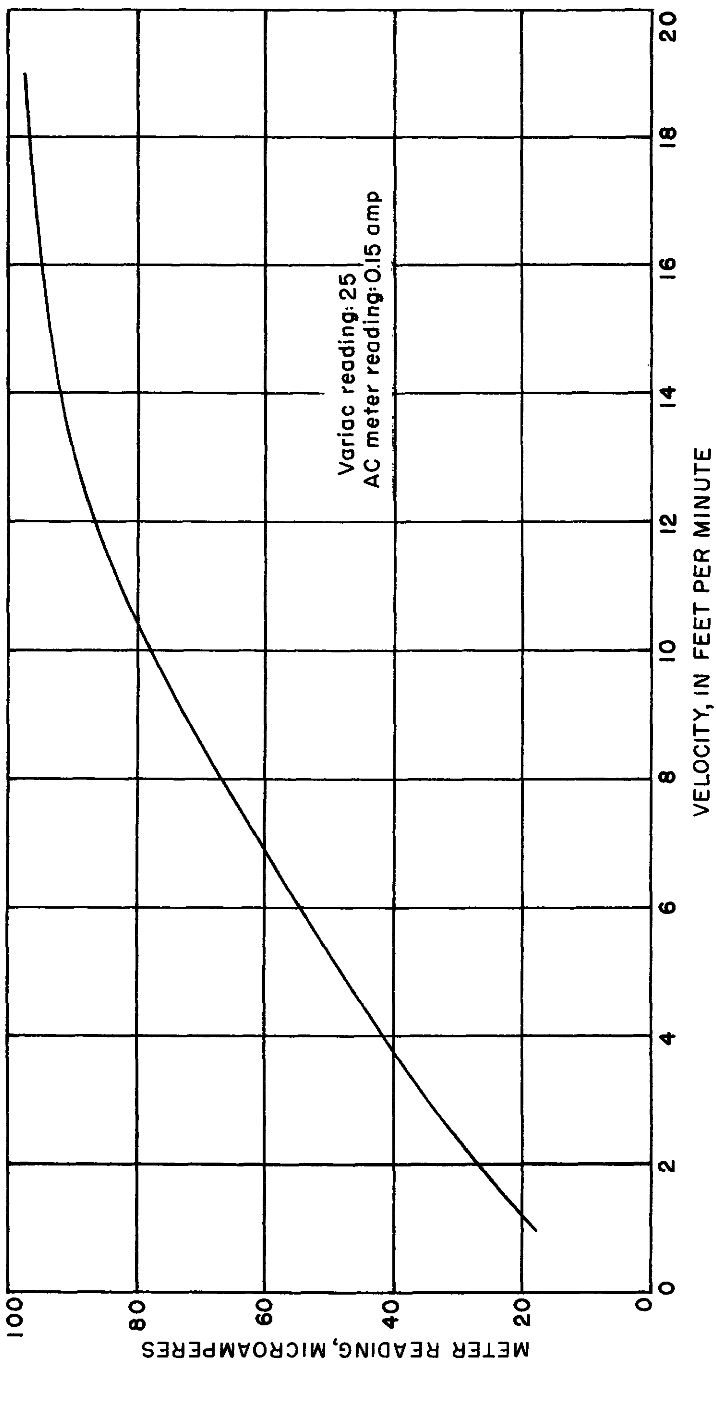
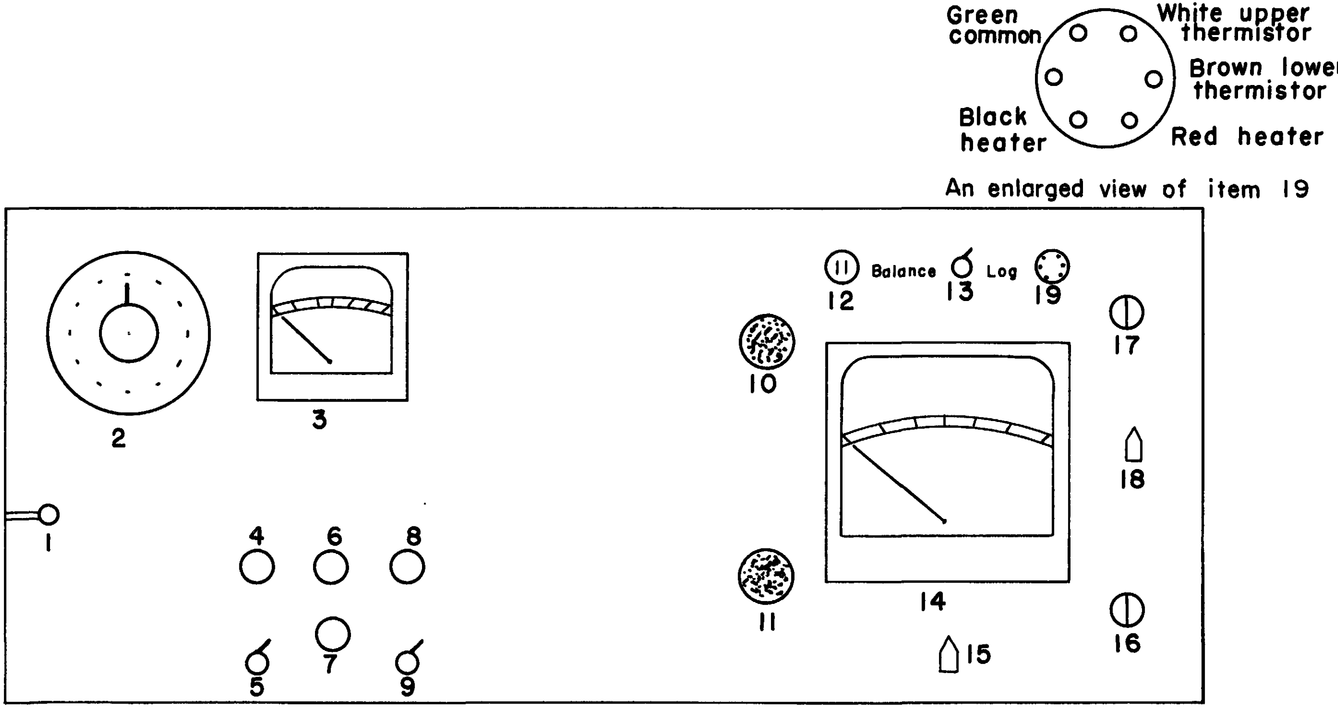


FIGURE 4.—Sample rating curve for determining velocity of movement from microammeter readings.



1. Line cord
2. Varlac
3. a-c ammeter
4. Varlac pilot light
5. Heat switch
6. Fuse
7. Fuse
8. Instrument pilot light
9. Power supply switch
10. Vent
11. Vent
12. 6-volt-battery input
13. Bridge-balance and log switch
14. Microammeter
15. Amplifier adjustment
16. One branch of bridge (screw-driver adjustment)
17. One branch of bridge (screw-driver adjustment)
18. Bridge-balance adjustment
19. Plug input from sensing unit

FIGURE 5.—Sketch showing components of instrument panel for thermal flowmeter.

box is the type having a removable tray in the top. The tray is removed and the electronic panel is mounted on the brackets formerly used to hold the tray.

The Variac (variable autotransformer) controls the heat output of the heating element. The resulting amperage is read on the a-c ammeter. The difference between the electrical currents flowing through the two thermistors is amplified so that it may be read more accurately on the microammeter. The amplifier is the differential type, with unit voltage gain. Its main purpose is for power gain; but, if desired, it could also drive a recorder.

OPERATION OF INSTRUMENT

The following procedure and instructions are recommended for logging with the pilot model of the experimental sensing unit. Numbers in parentheses refer to numbers on figure 5. Before logging is begun, connect the commutator line from the reel to the instrument receptacle (19) and plug in the line cord (1) to a 110-volt 50-60-cycle line. Then lower the thermal sensing unit into the water in the well to be logged. *Before turning on power or heat switch, follow procedures 1 and 2.*

1. Plug 6-volt battery lead into receptacle (12) and move bridge-balance and log switch (13) to the left to the word "balance."
2. Adjust microammeter (14) to zero, with bridge-balance potentiometer (18). Screwdriver-adjustment potentiometers (16) and (17) should be turned as far clockwise as possible unless unable to adjust with bridge-balance potentiometer (18).
3. Turn power-supply switch (9) on and allow 20 minutes for warmup.
4. Move bridge-balance and log switch (13) to the right to the word "log." Adjust microammeter (14) to 100 with the amplifier-adjustment potentiometer (15).
5. With Variac (2) turned to extreme counterclockwise position, turn on heat switch (5).
6. Adjust to desired heat with Variac (2). The a-c ammeter (3) registers the amount of current, which may be converted in terms of heat.
7. The velocity is determined on the rating curve by finding the value of velocity that corresponds to the microammeter (14) reading. Figure 4 is the rating curve for the pilot model of the thermal sensing unit.
8. Check instrument balance at intervals by turning heat switch off and allowing time for thermal sensing unit to cool. Microammeter (14) should return to a reading of 100. If not, readjust

instrument as in procedures 1, 2, and 4. Leave power-supply switch (9) on during this procedure to avoid warmup delay. Turn heat switch (5) on and read.

9. Turn heat switch (5) off when thermal sensing unit is out of the water, or the unit may be damaged.
10. Be sure to remove 6-volt battery plug when logging is finished.

RESULTS

A laboratory-constructed well, in which the vertical velocity could be controlled from 1 to 130 fpm, was used for testing several thermal sensing units. Each sensing unit required individual calibration. Although individual units may appear to be identical in construction, the velocity curves differ, probably because of differences in the electrical components or in the construction of the unit.

The individual calibration applies only for the laboratory conditions and setup used. Adaptation to field use requires some modifications, such as centering devices and flow-channeling devices, to cope with the conditions peculiar to the site. An excellent discussion of some of the problems involved in the field use of a thermal flowmeter, and the techniques employed to overcome them, is given in a paper by Patten and Bennett (1962).

Figure 4 shows the rating curve for one particular sensing unit having a 3/16-inch ID bore through the heating element. Only one heat range, 0.15 ampere a. c., was used for this sensing unit. The higher temperatures produced by 0.2 or 0.25 ampere a. c. caused the sensing unit to become unstable at low velocities, and reliable readings were difficult to obtain for velocities less than 14 fpm. Sensing units having bore diameters greater than 3/16 inch through the heating element were tested in various heat ranges, and separate rating curves were made for each. Measurement of high velocities required more heat from the heater, and baffles for mixing the heated water in the bore of the heating element to provide uniformly heated water. The readings, or velocity determinations, in the velocity ranges higher than 20 fpm have not been completely reliable, but enough work has been done to indicate that satisfactory results could be obtained by redesigning the heating element for more thorough mixing of heated water.

The ability of the sensing unit described in this report to compensate for the temperature changes at different depths in the well bore was determined by dropping the temperature of the water 17°F at a known rate. The instrument responded with identical water-velocity readings time after time.

Direction of flow, whether up or down a well bore, also could be detected with a properly designed sensing unit. Detection of downward flow was tried with the sensing unit described in this paper, but the detectable velocity range was found to be restricted to 7.5 to 20 fpm. The problem of measuring flow direction should be considered in any future experimentation and development.

The vertical flowmeter described here is potentially an important aid to geologists and hydrologists—first, because it is capable of logging extremely low velocities, which heretofore have not been detectable; and second, because of its small diameter, which permits it to be used in wells containing pump columns. The pilot instrument described is reliable in the low-velocity region; it is believed that this reliability could be extended to higher velocities by further experimentation in design. Eventually it may be possible to incorporate all the features needed for low and high velocities into a single sensing unit.

REFERENCE

Patten, E. P. and Bennett, G.D. (1962), Methods of flow measurement in well bores: U.S. Geol. Survey Water-Supply Paper 1544-C, 28 p.

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