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Technical Note

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APPLICATION OF HOT-WIRE (-FILM) FLOWMETERS TO WATER VELOCITY MEASUREMENTS IN WELLS

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ABSTRACT

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Hot wires have long been used for the measurement of air speeds, where they are particularly suitable for relatively small velocities. Unfortunately, it has not been possible to use them in water with the same precision and ease as in air. One of the main drawbacks of hot wires (films) when they are used in water measurements is that they become unstable because of the contamination of the wire (film) by dissolved gases, dirt and chemicals in the water, and they are very sensitive to ambient temperature fluctuations.

The present paper discusses the practical problems in using the hot-wire (-film) flowmeter for velocity measurements in water wells.

INTRODUCTION

Flowmeters are very useful in determining the magnitude of the velocity and direction of movement of water in a well at all depths.

From the flowmeter log we can identify and evaluate inflow levels, leaks in cased wells and aquifers tapped by cased wells having multiple screens. Hence, the use of flowmeters is essential in the solution of many hydrogeological problems.

Because the velocity regime under natural flow conditions is usually between 1 and 50 mm/s some useful results might be expected from the use of hot-wire flowmeters which are particularly well suited for very low velocities in air (Dring and Gebhart, 1969).

The first attempt to measure water velocities with hot wire known to us was published by Worthington and Malone (1917). They made some measurements on a vertical wire, 20 cm long and 0.025 cm in diameter, which they rotated in a tank of water. Their results were erratic at velocities below 60 mm/s as a result of the eddy currents set up by the wire and its holder.

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Davis (1922) published the most comprehensive data yet taken with fine wires in liquids. Richardson and McQuivey (1968) mentioned the use of hot wires for the measurement of water velocities in open channels.

The development of hot-film probes to replace the wire has eliminated the instability which results from electrolysis of the wire and conductivity of the water. Recently, there has been a continual increase in the use of such sensors in various geotechnical problems (Harold and Thomas, 1972), but only recently attention has been focused on the special problems arising in water (Fabula, 1968; Shaukatullah and Gebhart, 1977; Castaldini et al., 1980).

THEORY

A brief discussion of the theory of hot-wire (-film) flowmeters will be given to facilitate a general understanding of the measuring principle. The hot-wire (-film) flowmeter is a resistance—temperature transducer. The wire (film) is heated above the temperature of the surrounding water by passing an electric current through it. Flow of the water over the heated sensor cools it by forced convection. The rate of cooling is a function of the velocity of the flow; temperature, density, viscosity and thermal conductivity of the water; and temperature, diameter and length of the sensor. If all but the velocity are kept constant then the hot wire (film) may be used to measure the flow velocity.

There are two methods of operating the hot-wire (-film) flowmeter; either by passing a constant current through it and measuring the fluctuation of the electrical resistance with velocity fluctuation, or by keeping the temperature of the sensor constant, by using an electrical feedback system, measuring the current fluctuation with fluctuating velocity. The constant-temperature method is easier and the following description is based upon the constant-temperature hot-wire flowmeter.

The theoretical analysis of the device was published by King (1914), who first derived an expression for the heat convected from a cylinder submerged into a moving fluid. For the case of continuous incompressible flow, the best experimental relation between mean heat loss and mean velocity is:

$$I^2 R_f^2 / R_a^2 (R_f - R_a) = A + BV^n \tag{1}$$

where

R_f = electrical resistance of wire at wire temperature
R_a = electrical resistance of wire at ambient temperature
I = electric current flowing through the wire (film)
A, B, n = constants
V = water velocity

Eq. 1 can be written as

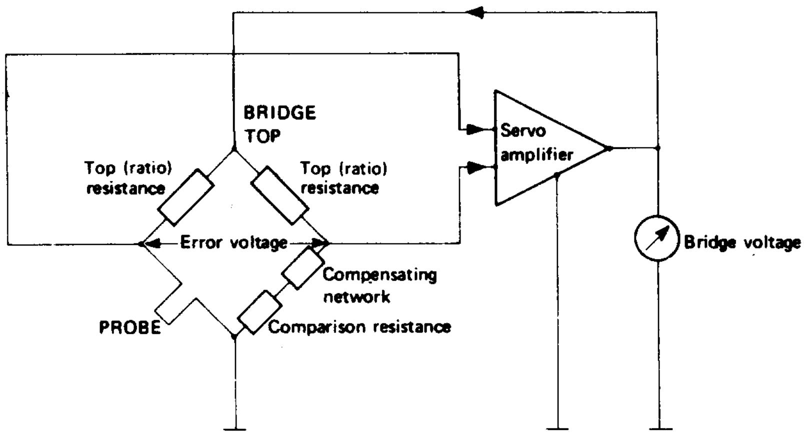

Fig. 1. Hot-film constant-temperature flowmeter bridge circuit.

$$\bar{E}^2 = R_a^2 K(K-1)(A+BV^n) \quad (2)$$

therefore

$$\bar{E}^2 = A' + B'V^n \quad (3)$$

where

$\bar{E}$ = mean bridge voltage (Fig. 1)
$K = R_f/R_a$, the overheat ratio

For $n = \frac{1}{2}$, one takes the original King's law form and for $n \neq \frac{1}{2}$, one can speak of a generalized King's law form. The value of n is of interest because bridge voltage linearizers produce a voltage proportional to V by, in effect, solving eq. 3 for V.

HOT FILMS — PROBE DESIGN

Hot-film sensors are more rugged and resistant to impact than hot-wire sensors; thus they are more amenable to the down-hole environment. Hot-film sensors are constructed by fusing a thin platinum film (or other suitable metal) on a ceramic or quartz substance. A thin coating of silica is deposited over the sensor to isolate it physically and electrically from the water. Typical sensors are shown in Fig. 2 and are known as conical, cylindrical or wedge-film sensors. Conical sensors tend to be self-cleaning and shed foreign particles.

PROBLEMS IN THE USE OF HOT-WIRE (-FILM) FLOWMETERS FOR WATER VELOCITY MEASUREMENTS IN WELLS

The high electrical conductivity of water, its low boiling point, its tem-

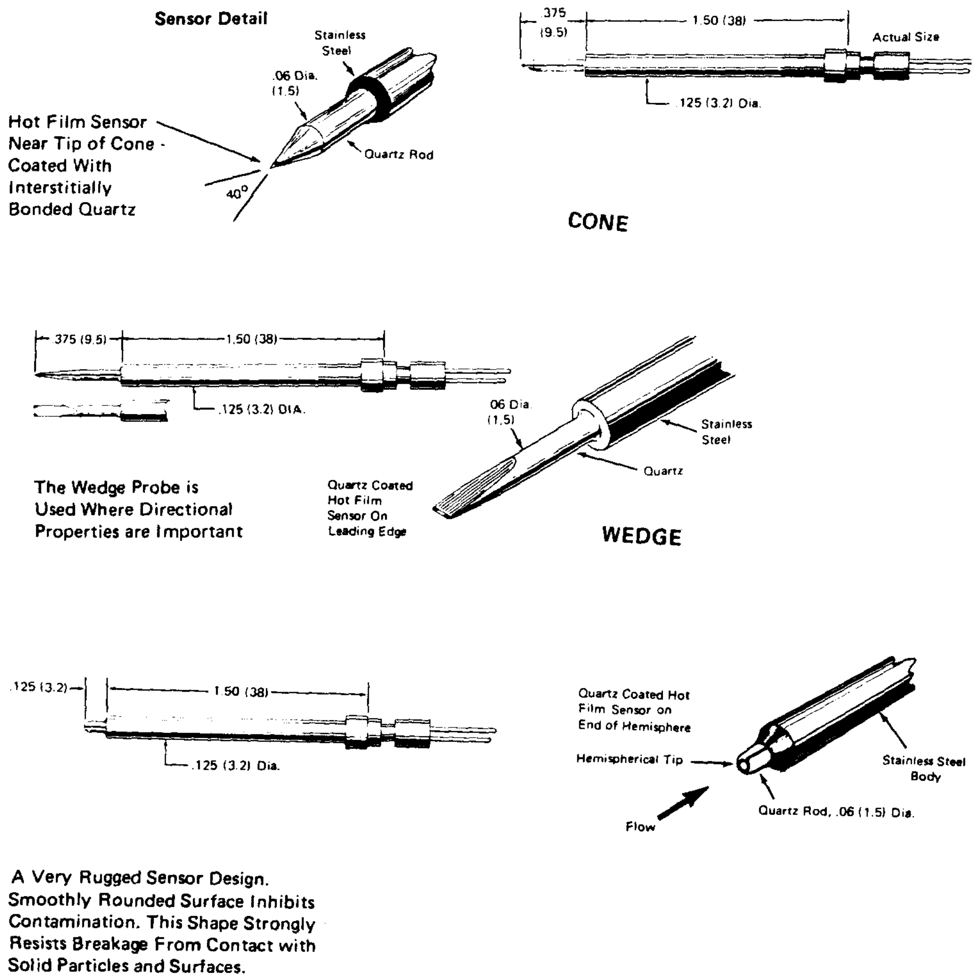

Fig. 2. Relative size and shape of hot-film sensors. (Dimensions in brackets are in millimetres, others are in inches.)

perature-dependent viscosity, and the large number of suspended particles found in well waters are some factors which make the behaviour in water of the hot-wire (-film) flowmeter very complicated. Our own experience in using the hot wire in water has not been very encouraging. It is essential when using a D.C. current to insulate the wire from the water, which is not easy, or to operate the instrument with less than ~1-V drop on the wire, in order to prevent electrolysis. Another problem is that since the wire (film) is hotter than the ambient water the solubility of air in the water is reduced near the wire. This means that bubbles of air form at the sensor and stick to it, thus changing the thermal conditions and considerably altering the calibration. The only means of eliminating these difficulties is to operate the meter at very low temperature. Another major drawback of the hot-wire (-film) flowmeter in its use in water is the serious problem of contamination of the film surface by small solid particles in suspension in the water of the well.

Measurements in the dirty water of a well can cause large changes in the calibration of the device. Deposition of a layer of dirt on the wire (film) will alter its frequency response as well as the mean calibration. The smaller the sensing element, the sooner the thickness of the deposit will reach an appreciable fraction of its diameter. The deposit is usually confined to the upstream side of the sensor near the stagnation line; for this reason, it is preferable to use sensors in the form of wedges or cones.

Recently, a method was developed (Richardson and McQuivey, 1968), for using the hot-film flowmeter in extremely dirty water. Their method is based on a hypothesis that dirt and air bubbles accumulating on the sensor decrease the mean voltage for a given velocity, but in the domain of frequencies encountered in water, do not affect the frequency response of the sensor to velocity fluctuations. For a given sensor, there is a unique family of voltage—velocity relations which can be defined by calibration with different overheat ratios. Although this method is very useful for the measurement of turbulence in water, it is of little help if we want to make measurements of absolute flow velocity in water wells.

Another problem which affects the operation of the hot-film flowmeter in wells is that the water-temperature variations in the well may significantly alter the temperature difference between the hot film and water. Rose (1962) considered the response of a linearized hot wire in air to small ambient temperature fluctuations. Sandborn (1961) indicated that fluid-temperature fluctuations significantly affect results in many modes of operation. Resch and Coantic (1969) found it necessary to calibrate for fluid-temperature variations in water. Newman (1966) calibrated film probes in water at various temperature levels; his results show that fluid-temperature variations cause significant variation in the output of the device.

From the above, we can say that calibrating hot wires (films) over an adequately large range of ambient fluid temperatures and in the environment of a groundwater well is extremely inconvenient and difficult, especially when water temperature differs greatly from ambient laboratory conditions. Moreover, large temperature differences induce appreciable natural convection effects in the water.

An additional error which is induced by water-temperature fluctuations, arises from water property variations. It is known that variations of the viscosity and the density of the water can significantly vary the calibration results.

CONCLUSION

Hot-wire (-film) flowmeters are by no means a panacea for wellbore fluid-flow measurements; but the device could be valuable if it could be made to work accurately in water. Its sensitivity increases with decreasing velocity, it could therefore be used to great advantage to measure those low velocities where an impeller flowmeter is not satisfactory. Unfortunately there are many problems to be solved and up to now thermal flowmeters can be considered to be of little practical value for water velocity measurements in wells.

Presently, a new device is under theoretical and experimental investigation in this laboratory, and has shown considerable promise in water velocity measurements as low as 1 mm/s. It uses the thermal wake of a heated wire, submerged in the water as a tracer. Important advantages of the heat-pulse method are its stability and repeatability over a wide dynamic range in a wide variety of conditions.

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