Two Temperature-compensated Thermistor Current Meters for Use in Marine Ecology[1]

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ABSTRACT

Small bead thermistors of the type commonly used for temperature measurement can be adapted for use as current probes in liquid or gaseous media. The small size, the rapid response, and the sensitivity of such probes make them well suited for the study of water movement as a microclimatic factor in marine and limnic habitats. Two types of flow meters have been built, tested, and calibrated: (i) one with a directly heated thermistor for work where minimum size of the probe is important, and (ii) one with a thermistor heated by an outer wire coil, for use where higher accuracy is needed and stronger currents are expected. The useful working range in water is 0.2–250 mm sec^{-1} (i) or 1–1000 mm sec^{-1} (ii), respectively. Temperature compensation has been achieved for field work and laboratory experiments in which the temperature of the environment changes. The direction of a water current is not recorded by this device.

Introduction and Theory. Water movement is one of the most complicated and decisive factors in the sea. A great variety of instruments has been developed, mostly by oceanographers, to measure the water movement. The devices have ranged from propellers and similar mechanical instruments to hot-film instruments for measuring currents and turbulence in larger bodies of water. In recent times, the importance of understanding the structure of the microclimate that actually surrounds an organism and the need for metric data for an analysis of the parameters have been emphasized (Riedl 1964, Forstner and Rützler 1969).

Miniature thermistors have already been used for measuring the velocity of small quantities of liquids and gases in closed systems under conditions of

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constant temperature (Vepřek 1963). Such flow meters measure heat exchange between a heated solid body (thermistor) and a surrounding liquid or gaseous medium as a function of flow rate. Hotwire anemometers and similar instruments used in aerodynamics and meteorology work on the same principle. Our aim has been to adapt the use of miniature thermistors to the investigation of current patterns in very small areas.

Krause (1956), who has described a thermistor chain for measuring air temperature and wind velocity, has dealt extensively with the physical principles involved. Because the theory of the method is important for an evaluation of the results and because the original paper is not available to most workers, the essentials of Krause's equations are given here.

The heat exchange between a solid body and a surrounding medium is effected by heat conduction, convection, and radiation. The sum of the effects of these three factors is the heat-exchange coefficient, α, defined by

$$N = \alpha F(\vartheta - \vartheta_M), \qquad (1)$$

where N = total output of energy; F = surface of the solid body; ϑ = surface temperature of the body, assumed here, for the sake of simplicity, to be identical to that of the average temperature of the body; ϑ_M = temperature of the medium; αF = the heat-conduction coefficient. α is the sum of α_C and α_R; α_C is a measure of the heat exchange by convection and α_R is the heat transfer by radiation; α_R can be disregarded in this case, since the temperature difference $(\vartheta - \vartheta_M)$ is small and α_C is much larger than α_R in water; α_C can be represented empirically by

$$\alpha_C = c_1 v^n + c_2. \qquad (2)$$

c_1, c_2, and n are constants and v is the velocity of the medium. The heat conduction coefficient is important for the voltage-current characteristic of the thermistor (Fig. 1). From (1), $I = U/R$, and $N = IU$, we obtain the current, I, and voltage, U, in the thermistor:

$$I = ([\alpha F(\vartheta - \vartheta_M)]/R)^{1/2}, \qquad (3)$$

$$U = [\alpha F(\vartheta - \vartheta_M) R]^{1/2}. \qquad (4)$$

Since R is a function of ϑ, the $I - U$ characteristic is a function of the temperatures, ϑ and ϑ_M; further, according to (2), $I - U$ is dependent on the current velocity. Because of the dependence of the voltage-current characteristic on α, a thermistor can be used as a flow meter. Eqs. (1) and (2) show that

$$v = \left(\frac{\dfrac{N}{F(\vartheta - \vartheta_M)} - c_2}{c_1} \right)^{1/n}, \qquad (5)$$

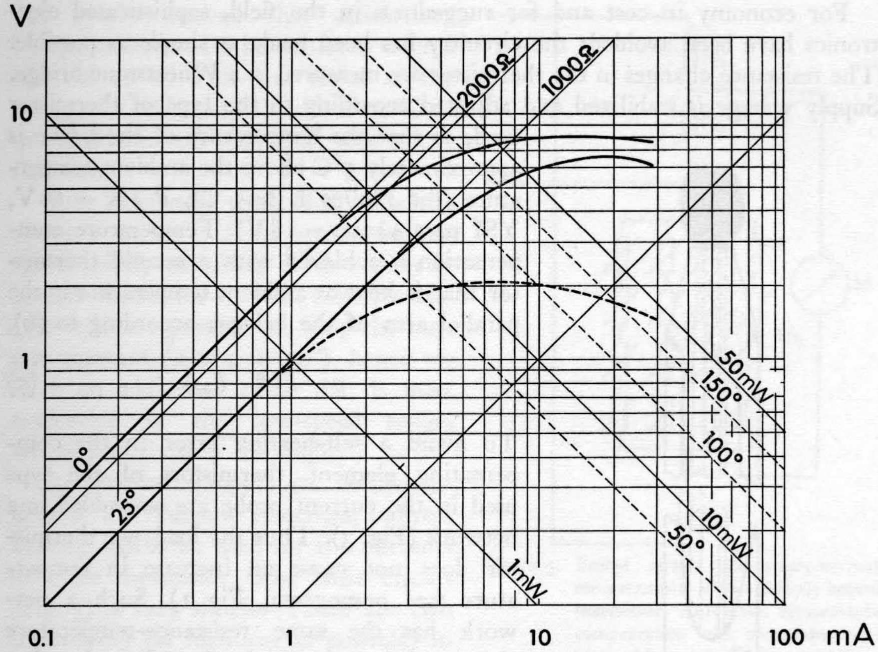

Figure 1. Nomogram demonstrating the relationship between current (mA), voltage (V), resistance (Ω), and temperature of a thermistor (1000 Ω at 25°C). Solid line for water, dashed line for air; medium at 0 velocity.

where N = the constant power dissipation and F = the surface of the thermistor (or its protective sheathing). Since N and F are constants, we write

$$v = \left(\frac{A}{\vartheta - \vartheta_M} - B\right)^{1/n}. \qquad (6)$$

The temperature difference between a heated thermistor and a thermistor at the ambient temperature of the medium is therefore a measure of the current velocity.

Directly Heated Thermistor Probes. Since the sensing element consists of the thermistor bead only, very small probes can be made with a suitable component (e.g., Philips E 205 CE P 1 K 1 mm Φ, YSI part Nr. 44003 2 mm Φ). The thermistor, mounted on top of a heat-insulating epoxy cone moulded onto the tip of a stainless-steel tube (Fig. 2), is dip-coated with a film of epoxy, which serves as electric insulation. This tube is mounted on the male part of a watertight cable connector equipped with a standard three-prong microphone plug.

For economy in cost and for ruggedness in the field, sophisticated electronics have been avoided; the circuitry has been made as simple as possible. The resistance changes in the thermistor are measured in a Wheatstone bridge. Supply voltage is stabilized and adjusted according to the type of thermistor used, so that the temperature of the probe is approximately 5°C above the ambient temperature (for Philips E 205 CE P 1 K = 10 V, YSI part 44003 = 18 V). Temperature compensation is achieved with a second thermistor that is kept at ambient temperature in the parallel arm of the bridge; according to (6),

$$v = F(\vartheta - \vartheta_M). \tag{7}$$

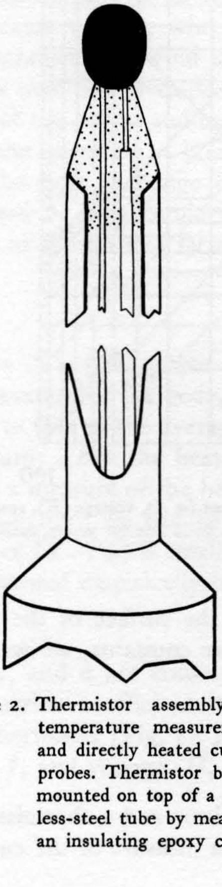

Figure 2. Thermistor assembly for temperature measurements and directly heated current probes. Thermistor bead is mounted on top of a stainless-steel tube by means of an insulating epoxy cone.

To avoid a self-heating error in the compensating element, thermistors of the type used in the current probe are assembled in a network (Fig. 3). Thus the load per thermistor does not cause an increase in temperature (see nomogram, Fig. 1). Such a network has the same resistance-temperature characteristic as a single thermistor but has a higher dissipation depending on the number of elements employed.

Benard (1967, and personal communication), in his littoral recording station, has achieved temperature compensation for the current meter by using a thermistor that provides ten times the nominal resistance (resistance in ohms at 25°C) of the current probe as temperature sensor. This simple space-saving arrangement did not give sufficient compensation for our more sensitive probes. Therefore, performance was improved by adding padding resistors (Fig. 4). R_1 and R_2 were fixed with 1 K and 10 K ohms respectively. (For lower temperatures of the medium, these values have to be decreased to keep the thermistor output constant.) For compensation, at any temperature, T_n,

$$R_2 R_{Th_v} = R_1 \left(R_s + \frac{R_{Th_T} R_p}{R_{Th_T} + R_p} \right). \tag{8}$$

Approximate values for R_s and R_p are found by substituting for R_{Th_T} and R_{Th_v} at the two extreme temperatures of the range desired. Evaluation of our results showed that satisfactory compensation could be achieved over a span of 10°C. This was tested in the range of 15°C to 25°C and of 20°C to 30°C. Maximum zero drift was ±3% full scale.

Both methods work for velocities above 1 cm sec^{-1} if the resistor values are carefully matched. With a directly heated thermistor in such a simple circuit it is not possible to keep the output constant (±2% in 10°), hence we have an additional error that is most noticeable in the low-speed range, where sensitivity is the highest.

For critical temperature compensation at low current velocities, indirect heating has to be used for the current-sensitive thermistor. The basic circuit (Fig. 5) is very simple. There are two thermistors (as identical as possible) in parallel arms of the bridge. The thermistors function as differential thermometers so that the condition of eq. (6) is reached. The difference in the temperatures (i.e., resistance) is therefore a measure of th əvelocity of the medium.

Fig. 6 shows the design of such a probe. A miniature thermistor is fastened with epoxy resin into a thin silver tube. A heating coil of oxidized constantan wire (0.03 mm Φ) is wound around the outside of the tube. The whole assembly is fitted into a thin-walled silver cone (filled with silicone grease for better heat conduction) and is mounted on a plastic tube (autoclavable grade). The probes built by us with bare Philips miniature thermistors have a diameter of about 2.5 mm. If a larger diameter can be tolerated, interchangeable (±0.5%) THERMOLINEAR ^{R} (YSI-

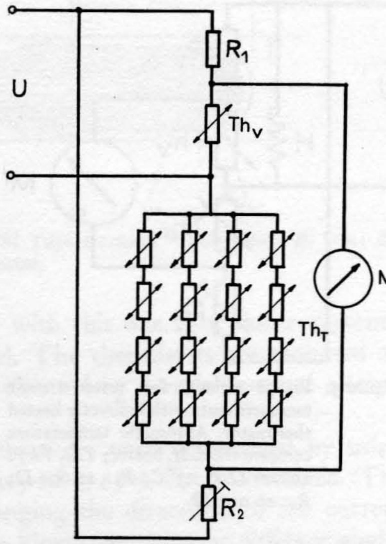

Figure 3. Bridge circuit for water-current measurements with a directly heated thermistor. Automatic temperature compensation with thermistor network. *M*, meter; Th_v, current thermistor (1000 Ω at 25°C); Th_T, temperature thermistor (1000 Ω at 25°C); R_1: 500 Ω; R_2: 1000 Ω; *U*, supply voltage.

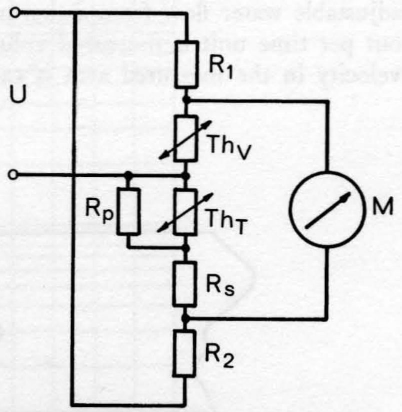

Figure 4. Bridge circuit for water-current measurements with directly heated thermistor and automatic temperature compensation. Th_v, R_1: 1000 Ω; Th_T, R_2: 10 000 Ω. R_s, R_p, padding resistors.

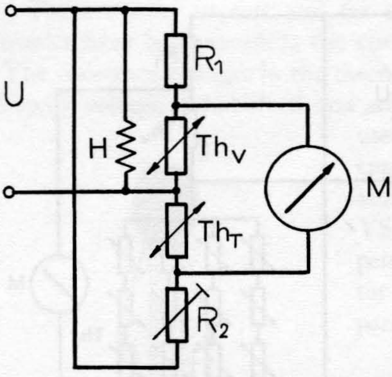

Figure 5. Bridge circuit for water-current measurements with indirectly heated thermistor. Automatic temperature compensation. *H*, heater; Th_v, Th_T: 10 000 Ω at 25°C; R_1: 10 000 Ω; R_2: 20 000 Ω.

components) thermistors can be used; Fig. 7 shows the somewhat modified mounting of such a component. The diameter of the finished probe is 4.5 mm, but calibration is simpler, since these compound thermistors have a linear resistance-temperature relationship.

Probes of the above type have a much slower response than directly heated probes. Characteristic time constants (70% of new value) vary between 5 and 10 seconds. This is not a drawback in the low-speed range, where changes in current occur only gradually.

Even if all the electrical parts are carefully matched, we have found it necessary to calibrate the finished probes, since uniformity of manufacture could not be achieved with our simple workshop methods.

Calibration. The calibration arrangement for velocities up to 10 cm sec^{-1} is rather simple. The current probes to be calibrated are inserted through the side of a plastic tube of known diameter (about 2 cm Φ to avoid boundary-layer effects). A centrifugal pump and a two-way stop-cock deliver a continuously adjustable water flow from a thermostat tank. The amount of water flowing out per time unit is measured volumetrically; from these values the current velocity in the measured area is calculated. If an already-calibrated probe is

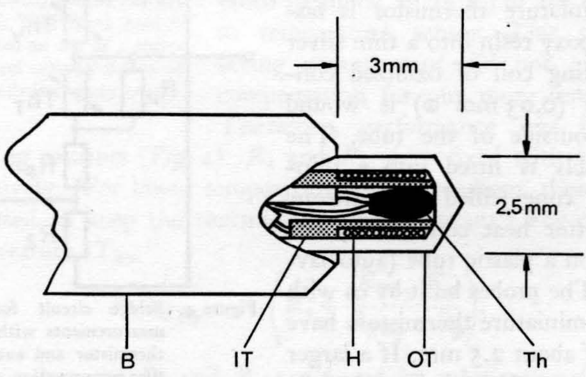

Figure 6. Indirectly heated current probe with miniature thermistor (Philips B 8 209 CE P10K). *B*, base; *IT*, inner silver tube; *H*, heater; *OT*, outer silver tube; *Th*, thermistor.

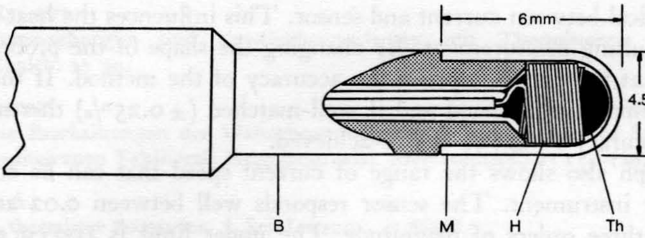

Figure 7. Indirectly heated current probe with YSI THERMOLINEAR *R* thermistor. *B*, base; *M*, protective mantle; *H*, heater; *Th*, thermistor.

available, all the others can be compared with this one. For faster currents, calibration is done in a measuring channel. The thermistors are mounted on a trolley, which can be pulled across the channel by a variable-speed electric motor.

The diagram in Fig. 8 shows the calibration curve determined by using a variable-speed electric motor. An accuracy of ± 15% can be obtained. The largest part of the error is caused by changing the directions of the current with respect to the conical probe, since the kinetic structure at different angles

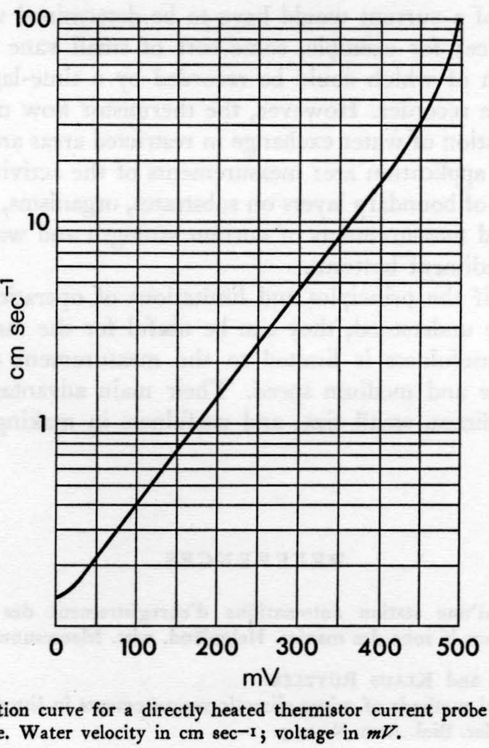

Figure 8. Calibration curve for a directly heated thermistor current probe at constant water temperature. Water velocity in cm sec^{-1}; voltage in *mV*.

is not identical between current and sensor. This influences the heat exchange and the resulting measurement. By changing the shape of the probes, we are attempting at present to improve the accuracy of the method. If the current direction remains unchanged and if well-matched ($\pm 0.25\,\%$) thermistors are used, an accuracy of $\pm 5\,\%$ can be achieved.

The graph also shows the range of current speed that can be covered by our present instrument. The sensor responds well between 0.02 and 25 cm sec^{-1}, i.e., three orders of magnitude. The upper limit is 100 cm sec^{-1}, but the sensitivity decreases quickly in fast currents.

Applications and Conclusions. With the device described here it is possible to identify only the velocity of water particles and the character of their motion, not the direction of the current. Unidirectional water movement appears on the recorder as a distinct line, since the velocity changes occur slowly. In the case of oscillating bodies of water, in each period the values will pass from 0 to the maximum. On the chopper type recorder (one dot every two sec.) used by us, these values appear as a more or less wide scattering of dots, depending on the time constant of the probe and the oscillating frequency of the medium.

The direction of a current would have to be determined with the help of an additional device; for example, some sort of small vane attached to the probe, the position of which could be recorded by a time-lapse camera synchronized with the recorder. However, the thermistor flow meter was developed for determination of water exchange in restricted areas and microhabitats. Some examples of application are: measurements of the activity of filter feeders, determination of boundary layers on substrates, organisms, or experimental tow structures, and measurements of current strength and water exchange in rock crevices or sediment bottoms.

In conclusion, if the principles and limitations of operation of thermistor current meters are understood, they can be useful for the marine and limnic ecologist. Their usefulness is limited to the measurement of currents and turbulences of low and medium speed. Their main advantages are: ease of construction, sturdiness, small size, and usefulness in making permanent recordings.

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