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A simple thermo-electric probe for the measurement of low water flow

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Abstract

A probe for the measurement of thermal conductivity in porous materials (e.g. soils) has been modified and used as a sensor to measure the flow rate of water in the range of 0.5 to 5 mm s^{-1}. A repeatability of 5 % of the measured flow rate in water was obtained.

Keywords: low water flow, water movement

Introduction

In ecohydrological research in peat lands, several parameters are of interest. In addition to vertical temperature distribution, water conductivity, water level differences etc., knowledge of water movement in the peat is of great importance, especially where potential contamination problems by seepage from adjacent open water exist. In the present case, water velocities were expected to be in the range of a few mm s^{-1} or less. The problem was the arrangement of, at notice, an inexpensive sensor with which a rapid measurement could be made, in order to verify this assumption. In general, commercially available flowmeters do not cover this low range or have sensors which are not robust enough to withstand normal manipulations during field work. Daniels et al. (1977) described a sensor with a measuring range of 2 to 300 mm s^{-1} which might be suitable to our purpose. The principle depends on the cooling of a heated body, consisting of a cylinder with a length of 65 mm and a diameter of 6 mm. A constantan wire, wound around the cylinder if partially galvanized with a copper layer, resulting in a thermopile with 80 thermocouples. We tried to build this type of sensor but we were not very successful in reaching the sensitivity as found by Daniels et al. (1977). Once having an experimental set up, it was easy to do measurements with another sensor we had already at our disposal. That sensor was normally used for the measurement of thermal conductivity in soils (Janse & Borel, 1965). The results of these investigations are presented below.

Materials and methods

Measuring method

The thermal conductivity probe consists of a stainless steel needle with a diameter of 2 mm, containing a heating wire over its full length and a thermocouple at the center of the needle. For its normal use the probe is inserted in the soil and is heated during a periòd of time. After the heating current has been switched off, the cooling rate of the probe is used as a measure for the heat conductivity of the soil in question. For a known soil the heat conductivity is also a measure for the water content of that soil.

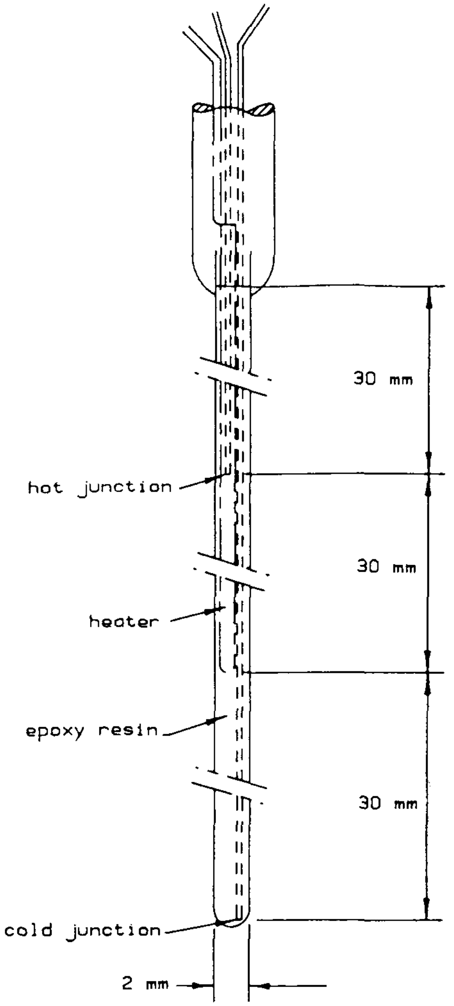

Fig. 1. The probe, with isolated heating wire and warm and cold thermocouple junctions.

Initial successful measurements of water velocity were made with a combination of two such probes, the first of which was heated and the second one was used to compensate for water temperature. In stead of the cooling rate the maximum output signal was taken as a measure for water velocity. Because a measuring method with two probes is not so convenient, the next step was to build the temperature compensation in the sensor. The new probe consists of a length of 90 mm of a capillary tube with an outer diameter of 2 mm and an inner diameter of 1.6 mm, closed at the end.

In the upper part of the tube an isolated constantan heating wire with a diameter of 0.1 mm and a resistance of 12.4 ohms is situated. The temperature rise is measured with a copper-constantan thermocouple with a thickness of 0.1 mm. The hot junction of this thermocouple is situated on half length of the heating wire. The lower part of the tube contains the cold junction of the thermocouple, to compensate for variations in water temperature. The tube is filled with an epoxy resin. Its total length is approximately 100 mm (Fig. 1).

Experimental set-up

The probe can be heated either continuously (stationary method) or intermittently (non-stationary method). Preliminary measurements showed that the stationary method yielded results that were affected by drift because the lower thermocouple warmed up after some time. We therefore decided to explore the non-stationary method. Both the duration of the heat pulse through the probe and the pulse interval could be varied (between 0 and 60 s, and between 0 and 150 s, respectively) with the aid of a simple electronic circuit. The current itself was set with the controls of the current source (Fig. 2). The current through the probe was measured with a digi-

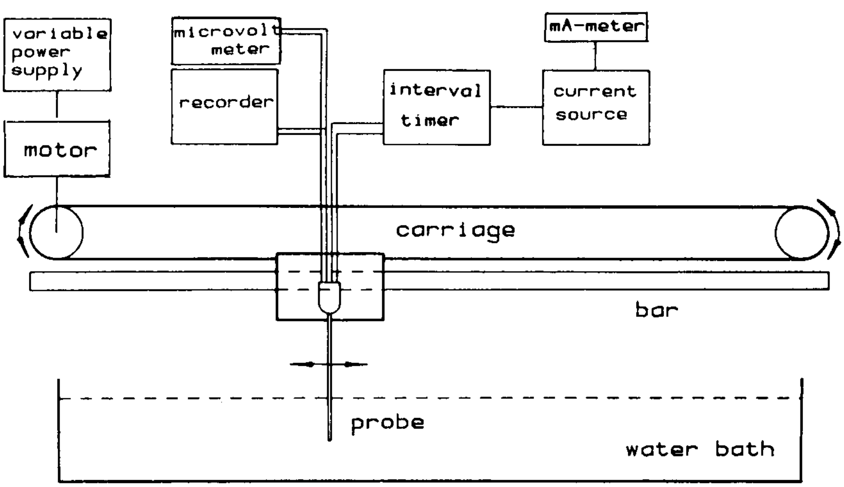

Fig. 2. Schematic diagram of the apparatus and instruments used.

tal multimeter, Hewlett Packard, model 3465 B. The probe was attached to a motorized carriage (Fig. 2), the speed of which was set with a variable power supply. The probe was immersed in a water bath 0.15 m deep, 0.15 m wide and 1 m long. The probe could be moved through the water at a speed of 0.2 to 100 mm s^{-1}, which was interpreted as an equivalent flow of water along the probe. The velocity was checked with a chronometer. The output of the probe was recorded on a sensitive potentiometric recorder (Kipp & Zonen, model BD5) with a smallest range of 20 μV full-scale. The output signal, which was in the range of 0 to 700 μV (0 to 17.5 K) was simultaneously measured with a microvoltmeter (Keithly, model 191). The temperature of the water was measured with a thermocouple and the microvoltmeter mentioned.

Theoretical considerations

It is obvious that the output of the probe depends on the power of the energy pulses. The output of the probe also depends on the heat transfer coefficient from the probe to its environment. This coefficient is a function of flow velocity. From theoretical considerations as given by Smith & Stammers (1977) the following relationship can be derived for a cylinder with infinite length in a transverse stream of water:

$$h = \frac{\lambda}{d} \, (0.42 \times \mathrm{Pr}^{0.2} + 0.57 \times \mathrm{Re}^{0.5} \times \mathrm{Pr}^{0.33}) \tag{1}$$

where:
h = heat transfer coefficient (W m^{-2} K^{-1})
λ = heat conductivity of water (W m^{-1} K^{-1})
d = cylinder diameter (m)
Pr = Prandtl's number
Re = Reynolds number = $d \cdot v/\upsilon$, where
v = water velocity (m s^{-1})
υ = kinematic viscosity of water (m^2 s^{-1})

Equation 1 is valid for Reynold numbers between 1 and 10^5.

Theoretically, for a probe of infinite length with a co-axial heating wire, the temperature rise ΔT in the centre of the probe, when a heat flux $d\phi/dt$ is generated, can be described by Equation 2 (VDI-Wärmeatlas, 4. Auflage, 1984):

$$\Delta T = \frac{d\phi}{dt} \left(\frac{1}{\lambda_1} \ln \frac{r_2}{r_1} + \frac{1}{\lambda_2} \ln \frac{r_3}{r_2} + \frac{1}{h \cdot r_3} \right) / 2L \tag{2}$$

where λ_1 and λ_2 are the heat conductivities of the epoxy resin and stainless steel, L is the length of the heated part of the needle and r_1, r_2 and r_3 are the radii as drawn in Fig. 3.

Equations 1 and 2 have been used to calculate the relationship between ΔT and water velocity v, at a given heat flux $d\phi/dt$.

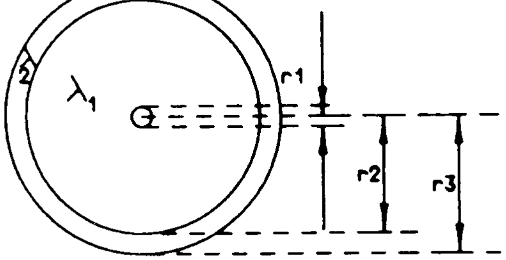

Fig. 3. Model used in Equation 2, where λ_1 and λ_2 are the heat conductivities of the epoxy resin and stainless steel, r_1 is the radius of the heating wire.

First, h as a function of v (Re) has been calculated from Equation 1. This results in Fig. 4. The values for λ, Pr and υ (Re) were collected from Grigull (1963). Second, ΔT as a functionof v, calculated with Equation 2 has been plotted in Fig. 5. For convenience, ΔT has been transformed to microvolts.

More detailed models of heat conduction through the needle to its environment have been described extensively by van Haneghem (1981) and Bruijn et al. (1983).

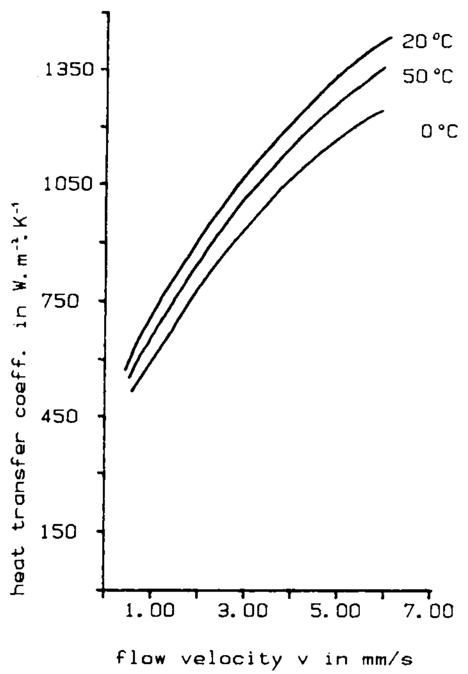

Fig. 4. Heat transfer coefficient h as a function of water velocity v (Equation 1).

Results

Laboratory results

Measurements were made at flow velocities near 0, 0.5, 1, 3 and 5 mm s^{-1}.

In Table 1 the first series of measurements is summarized. All figures are the averages of five separate determinations. A convenient pulse length was 30s, with an interval time of 60s. It meant that the output signal could reach its maximum value with no drift, without being affected by the previous pulse.

Figures 5 and 6 have been derived from Table 1. Fig. 5 shows the amplitude (A) in microvolts as a function of flow velocity (v). As may be expected, the output signal is proportional to the square of the heating current. The relative sensitivity hardly depends on the heating current, as can be concluded from Fig. 6, where the relative output (100 % at v = 1 mm s^{-1}) versus flow velocity is given.

The standard deviation, calculated from five measurements, is within 4 % at a velocity of 1 mm s^{-1}.

At velocities of 0.5 mm s^{-1} or less the output signal showed instability because of the effect of convection around the probe, due to self-heating.

Table 1. Output of the thermocouple as a function of flow velocity for different heating currents.

Heating current (mA)	Flow velocity (mm s^{-1})	Output amplitude (μV)	Standard deviation of five measurements (mm s^{-1})
148	0.0	94-102	–
148	0.5	92	0.005
148	1.02	81	0.038
148	3.05	66	0.164
148	5.00	60	0.240
225	0.0	218-230	–
225	0.5	214	0.017
225	1.00	190	0.015
225	3.13	154	0.165
225	5.20	141	0.161
300	0.0	366-392	–
300	0.5	368	0.022
300	0.99	336	0.026
300	3.04	271	0.156
300	5.16	249	0.180
400	0.0	620-660	–
400	0.5	615	0.042
400	0.92	571	0.032
400	2.94	468	0.060
400	5.25	425	0.240

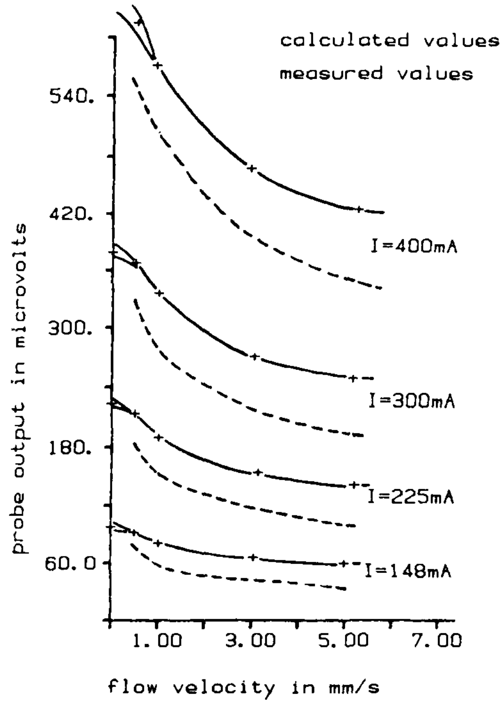

Fig. 5. Probe output A as a function of flow velocity v for different heating currents (pulse length 30 s, interval time 60 s).

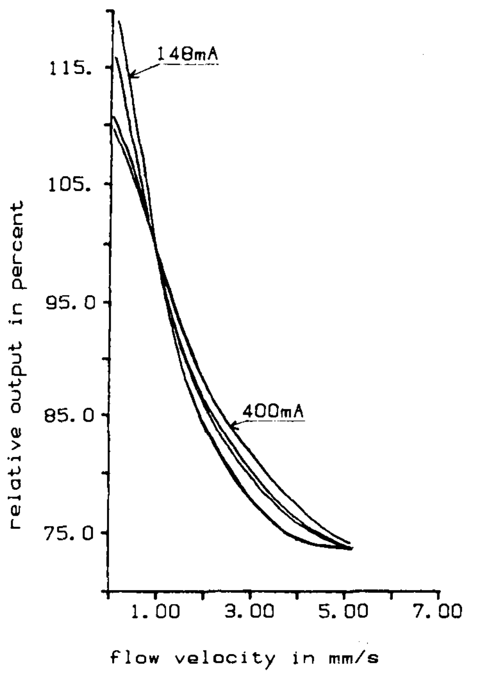

Fig. 6. Relative output versus flow velocity (1 mm s^{-1} = 100 %) derived from Fig. 5.

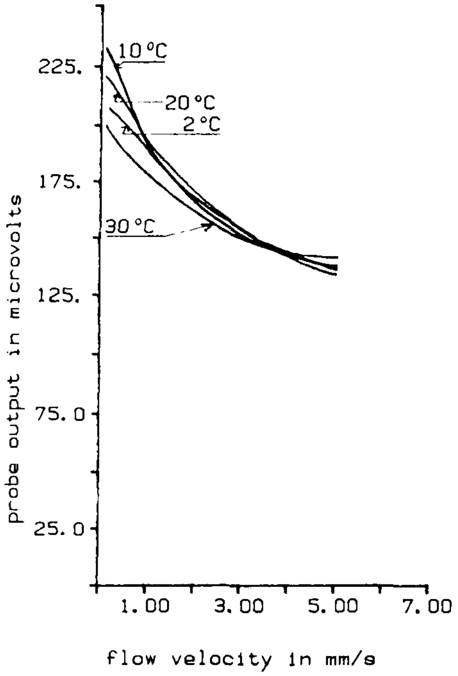

Fig. 7. The relation between water velocity and probe output for different water temperatures.

In order to verify the influence of water temperature, measurements were made with water temperatures between 2 °C and 30 °C. To that purpose a long, narrow aluminium container was placed in the water bath mentioned before. The water outside the narrow bath was stirred and thermostatically controlled. The results are given in Fig. 7. For all measurements, the heating current was 225 mA. For flow velocities above 1 mm s^{-1} the influence of temperature was less than 5 % of the mean value, below 1 mm s^{-1} the effect was up to 10 % in ΔT.

Field results

Measurements in 'de Weerribben' were made in a ground where an upper layer of about half a meter of peat is floating on water with a total depth of about 1.8 meter, with a muddy mass on lower depths. The probe was attached to an iron bar with a length of 2.5 m and a diameter of 18 mm, protected by a tube with a length of 2.3 m and a diameter of 20 mm. After penetration of the probe to the desired depth the tube was lifted 20 cm to allow for the measurement to be made.

Measurements were made at several spots, to depths of 2 m, especially where seepage from adjacent areas could be expected. It appeared that the measurements could easily be disturbed by the vibrations of the upper layer, caused by the presence of the observer, or even a gust of wind which caused undulatory motions. These motions resulted in an oscillating output signal of less than 400 μV, with a heating current of 400 mA. Once the equilibrium situation had been reached, at no spot an output signal of less than 620 μV was measured. This meant that non-zero velocities, if present, were less than 0.5 mm s^{-1}. It also meant that initial assumptions about water velocities at that ground need revision and that another measuring method needs to be looked after. The field experiments showed good reproducibility at zero velocity, i.e. the variations in the output signal were within the region where convection around the probe by self-heating could be expected (620-660 μV). Measurements with a heating current of 150 mA also did not result in detection of any flow velocity. The water temperatures during the field experiments ranged from 6 to 12 °C.

Discussion

The non-stationary method as described is a compromise. Continuous heating of the probe would heat the reference junction in the lower part as well as the connections to stronger wires in the upper part of the probe, both giving rise to drift in the output signal. The length of the heat pulse was chosen to get a maximum output with neglegible drift.

The pulse interval was chosen such, that no influence of previous pulses was observed.

Comparison of the results with Equation 2 shows fair agreement between theory and experiment (Fig. 5). The Reynolds number ranges from 1 to 10, so Equation 1 is still valid. The length of the probe is not infinite as theory assumes, but as $d/L = 1/20$ this does not have any significance.

The measuring range of the probe is limited at the lower end because of convection around the probe due to self-heating. The temperature rise of about 2K with a heating current of 148 mA, could be decreased by decreasing the heating current, and using sensitive thermistors for the measurement of the temperature difference.

For the measurement of lower velocities, another thermal method is very promising. The method includes the measurement of the difference in temperature rise between two sensors, located at opposite sides of a heat source.

Fritsch & Tauber (1966) described the method for measuring the flow direction of water in a bore-hole. Byrne, Drummond & Rose (1967) measured fluid fluxes around 10^{-3} mm s^{-1} in this way. Recently, Melville et al. (1985) investigated a commercially available instrument, based on the same principle. Seepage velocities of 0.03 to 3 m day^{-1} ($4 \cdot 10^{-4}$ to $4 \cdot 10^{-2}$ mm s^{-1}) could be measured under controlled laboratory conditions.

The method has also been used in the sap flow meter developed at TFDL (Schurer et al., 1979).

Conclusion

The sensor as described is an inexpensive, robust tool to rapidly measure water velocities in the range from 0.5 to 5 mm s^{-1}, with a repeatability of 5 %. For the detection or measurement of lower velocities, another thermal measuring method, based on the travel time of a heat pulse, has to be explored.

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