

A Rotary Thermal Probe for Measuring Groundwater Velocity

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Abstract: A rotary thermal groundwater flowmeter was studied theoretically and experimentally, and its electrical model was used for searching a linear transference. The velocity measuring range was extended with respect to previous developments, and flow direction estimated by rotating the sensor head of the probe. This instrument was tested under laboratory conditions with the probe in contact with saturated sand and within standard plastic screens. Simulations suggested that the probe would work properly with high flow velocities arising in some groundwater remediation processes. Flow direction was estimated with a mean squared error of 1.3° and a standard deviation of 0.9°.

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INTRODUCTION

Some groundwater flowmeters are based on the application of heat by means of an electric heater. Water flow produces temperature gradients around the probe's heater that are detected by temperature sensors (thermistors) symmetrically placed at a given distance around the heater.

When heat is injected into a water-saturated soil and flow velocity increases, the hydrodynamic dispersion of heat also increases.^[1] If heat is delivered in the form of constant power pulses, the differential temperature pulse upstream and downstream of the heater will initially rise almost linearly with flow velocity, reaching a maximum and finally decreasing for flow velocities greater than approximately 60 m/day.^[2,3]

Flow velocity may thus be inferred from differential temperature measurements using this transference curve.^[4] If the power pulse delivered to the heater increases, so does the differential temperature peak, but the particular flow velocity for which the differential temperature pulse reaches its maximum remains virtually constant.^[3] The reason is that heat is hydrodynamically dispersed, which not only imposes a limit to the linearity of the transference but produces also a drop of the curve after reaching a maximum. Because of this, the conversion of a temperature difference into a flow velocity via a transference curve is progressively less valid as flow velocity increases. This behavior prevents the measurement range of flow velocity from being extended by merely increasing the value of the constant power pulse. This is a problem when dealing with groundwater remediation processes in steep, inhomogeneous soils where flow velocities are well beyond the measuring range of the above mentioned flowmeters. On the other hand, since the angular response of the sensor axes of these flowmeters is far from being cosinusoidal for high velocities, large errors arise in estimating groundwater direction from vector addition of the velocity components.^[4]

An alternative thermal method is proposed here for extending the measuring range of groundwater flow velocity in magnitude and direction. To compensate for the increase in heat dispersion, more energy must be delivered to the heater. One way of doing this is to keep the heater's temperature constant. When flow velocity increases, water removes more heat from the heater, but with the aid of an electronic control, additional power can be supplied to the heater to keep its temperature constant. In this way, the hydrodynamic dispersion of heat can be partially countered and the linear measuring range extended.

The first aim of this work was to search for a linear transference curve between flow velocity and the thermal parameters that allows high velocities to be measured. An electrical model was used to this end.^[3] In a second stage, a method was developed to determine flow direction in an accurate way.

EXPERIMENTAL

Model Results

The electrical model was useful to study the relation between the flow magnitude and the thermal (or electrical) parameters of the probe, allowing several hypotheses to be studied readily. A number of methods to extend the measuring range of flow velocity were analyzed. Three of them are presented and discussed below. Herein, a constant temperature step is defined as an increase in the heater's temperature that lasts beyond the end of the test. Instead, a constant temperature pulse is defined as lasting a few seconds; this allows the cooling process of the heater to be studied. The results follow.

Method of the Temperature Difference

The model's heater was excited with temperature steps between 10 and 20°C with respect to room temperature to study the relation between flow velocity, V , and the temperature difference, ΔT , upstream and downstream of the heater. Figure 1 shows the experimental transference of a probe excited with a constant power pulse, and that of a probe excited with a constant temperature step as obtained with the model. For comparison purposes both curves were normalized to the maximum ΔT . It is seen that for a constant temperature step the transference has a maximum at about 400 m/day, whereas for a constant power pulse the maximum of the transference is at about 60 m/day. This suggests the possibility of measuring velocities six times larger.

Method of Time Decay

If the heater is excited with constant temperature pulses, the corresponding temperature pulses at the thermistor downstream of the heater have heating and cooling slopes that depend on the flow velocity. In a real instrument the heating slope will also depend on the dynamics of the temperature control circuit, but the cooling slope will not. The model

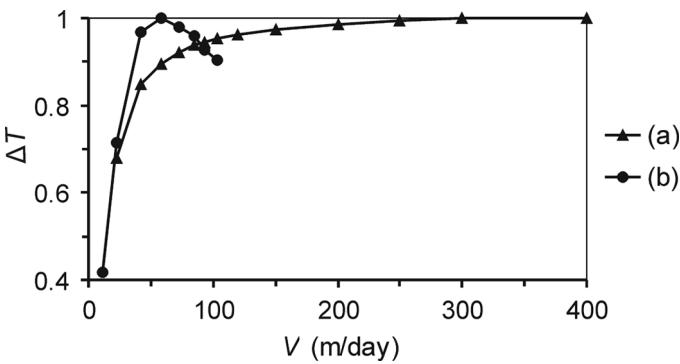


Figure 1. (a) Transference curve from a model simulation performed by keeping the heater excited with constant temperature. (b) Experimental transference curve of the probe with the heater excited with constant power pulse. Both curves are normalized to the maximum temperature difference between downstream and upstream thermistors.

was excited with constant temperature pulses, and the time t for the downstream thermistor to cool to 30% of its maximum temperature increment (decay time) was calculated. Because the heating and cooling processes follow exponential laws, this percentage was adopted in order to keep the temperature measuring errors as low as possible if a real instrument had to be constructed. It was found that the relation between the decay time t and flow velocity V is non linear and slightly sensitive for flow velocities greater than 80 m/day (Fig. 2).

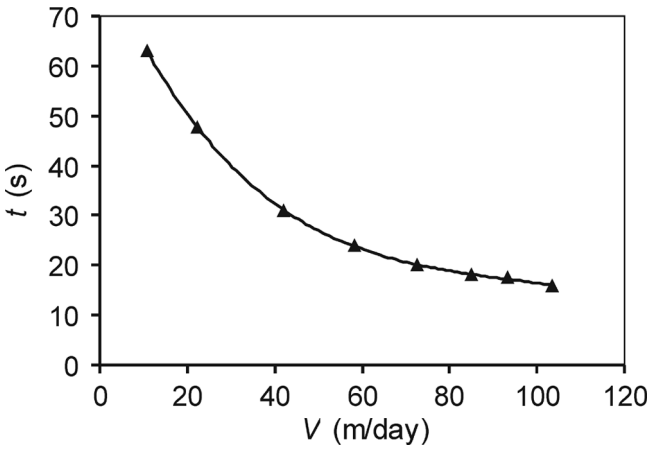


Figure 2. Time taken for a downstream thermistor to decay to 30% of its maximum temperature increment when the model is excited with constant temperature pulses.

Method of the Power Delivered to the Heater

The power required to keep the heater’s temperature constant depends on the flow velocity. For an increasing flow, water draws more heat from the heater and the power delivered to it must be increased. The relation between this power, P , and the flow velocity V is illustrated in Fig. 3 for temperature steps of 7, 10, 12, 13, 15, 18, and 23°C. The corresponding transference curves are well fitted by an essentially linear function in the flow velocity. This method seems promising for measuring flow velocity in the range 20–1000 m/day. For this reason it was chosen to be experimentally studied under laboratory conditions.

Materials and Methods

A probe was built with a central heater and four thermistors symmetrically placed around the heater and forming two orthogonal sensor axes (Fig. 4). Circuits were added for exciting the heater with constant temperature steps and for measuring the power delivered to it. For reasons that will become clear later, this set was called a rotary device probe (hereafter referred to as RDP) to draw a distinction between it and those having multiple sensor axes and excited with constant power pulses.^[2]

The four thermistors had metallic housings and were selected from a set of 15 in order that they might have similar characteristics. The wire of the heater was wound on to a fifth thermistor to measure its temperature and use it as a control signal. The metallic housing of this thermistor was electrically isolated with an epoxy resin to prevent the heater’s winding

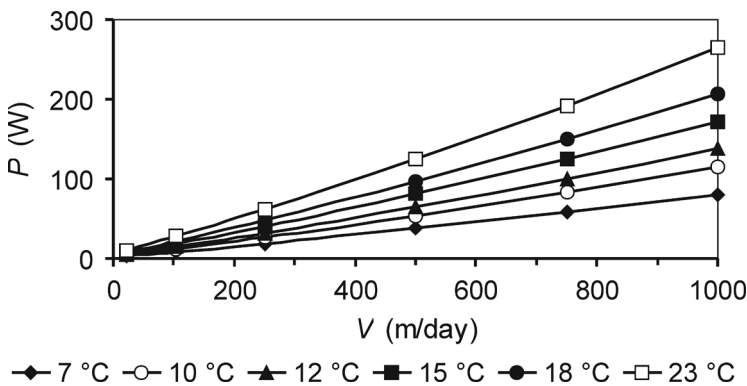


Figure 3. Power required for keeping the heater’s temperature constant as a function of flow velocity for temperature steps of 7, 10, 12, 13, 15, 18, and 23°C.

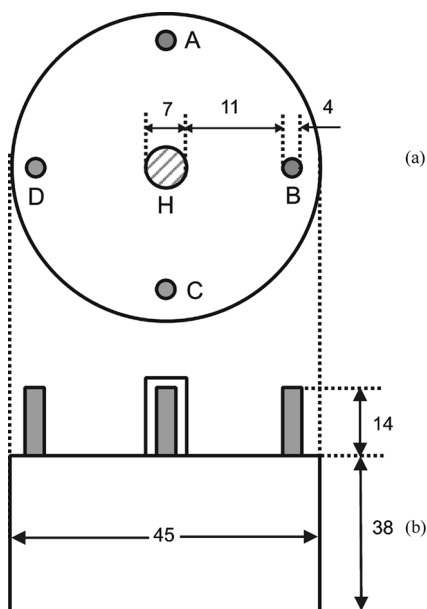


Figure 4. Schematic of the RDP probe with a central heater (H) and four thermistors (A, B, C, and D). (a) Top view; (b) side view. (Lengths in millimeters).

from being short-circuited. The whole set was covered with the same resin to protect the heater's wire from corrosion and hitting. The temperature was controlled through pulse width modulation (PWM) of a current source, the repetition period of the modulation being of a few milliseconds. The average heater current was registered. It was verified that the heater's temperature was stable within $\pm 0.05^\circ\text{C}$.

The RDP was calibrated in stirred water, and it was found that the differences in the measurements of the thermistors were less than 0.02°C . When the RDP was placed into a saturated porous medium and heat pulses were applied, its repeatability was about $\pm 3\%$; likely because of unstable contact between the medium, the heater and the thermistors. The dynamical response of the thermistors was analogous to that of another similar probe.^[5]

The RDP was then tested with the apparatus described elsewhere.^[3,5] Before the beginning of a test, water was circulated through the experimental tank waiting until the temperature of the four peripheral thermistors and the central one coincided. This was considered as the room temperature, and a temperature step was applied with respect to it.

The laboratory tests were conducted with the RDP in direct contact with saturated sand and with two types of standard plastic screens. One

of them (a 2-inch screen) had 60 and 52 mm external and internal diameters, respectively. It had three slotted columns with slot openings 45 mm long and 0.75 mm width, perpendicular to the screen axis and 6 mm apart. Due to manufacturing dispersions, the width of the zones without slots varied between 15 and 19 mm. The other screen (a 4-inch screen) had 125 and 120 mm external and internal diameters, respectively. Five equidistant slotted columns were distributed around this screen. The slots were 60 mm long, 0.75 mm width and 6 mm apart. The width of the zone without slots was 18 mm. When into the screens, the RDP remained completely surrounded with water because sand intrusion into the screens was avoided. Flow velocity inside a screen differs from that within the saturated porous medium, and it is related with the flow velocity outside the screen through a coefficient which, according to some works, ranges between 0.5 and 4.^[6,7]

The RDP was rotated 360° by hand in steps of 10° to study the angular response of its sensor axes in saturated sand. A temperature step was applied at each position, and a waiting period of about 150 s was adopted in order that the system might attain a steady state. These tests were conducted for flow velocities up to 100 m/day.

When tested inside the screens, after an initial transient, a constant temperature was reached at the heater and the RDP rotated by means of a direct current motor and a gear box. The angular resolution was set to 0.1° by the sampling frequency of the data acquisition system in order to obtain a manageable amount of data. For different tests the RDP was rotated with constant angular velocities between 0.0071 and 0.0098 rad/s.

RESULTS

Magnitude of Flow Velocity

The relationship between the power delivered to the heater and the flow velocity was studied experimentally under four conditions.

The RDP in Contact with Saturated Sand

The RDP was placed with one of its sensor axes parallel to the flow velocity. A temperature step was applied and the current delivered to the heater was controlled to keep the temperature constant. The flow velocity was varied in steps, waiting for a few minutes to allow it and the temperature of the heater and medium to reach a steady state. After more than 20 tests with different temperature steps, it was found that the relation between flow velocity and the power delivered to the heater was not as linear as predicted by the numerical simulation, but it was

observed a more linear relation with the heater's average current. Figure 5 shows the relation between flow velocity V and the heater's current I for temperature steps between 7.5 and 23.5°C for 160 test points. In order that all tests might be compared in one graphics the results were normalized to the value of the current for flow velocity 59 m/day for every temperature step. It is seen that the transferences can be approximated by two straight lines that intersect at a flow velocity of about 15 m/day. These two slopes are due to the thermal process and are analyzed below. The dispersion at both ends of the line with the smaller slope is because slopes increase with increasing temperature steps. The greater the slope, the more sensitive the method is. This imposes that a minimum accuracy must be attained in the electronic control of the heater's temperature to assure a certain degree of repeatability for the temperature step. To quantify the influence of the temperature step amplitude on the transference, the data from five series of temperature steps between 6.6 and 7.75°C were averaged, and the relation between flow velocity V and the normalized heater's current was fitted by a straight line (Fig. 6). The standard deviation for about 70 measured points was 5.5 m/day. These results suggest that even if the temperature step had a dispersion of $\pm 0.6^\circ\text{C}$, an instrument using this method would measure with reasonable errors for practical uses.

The RDP Within a 2-Inch Screen

Initially the screen was placed such that the whole slotted area faced the water flow. The transference between the heater's current and the flow

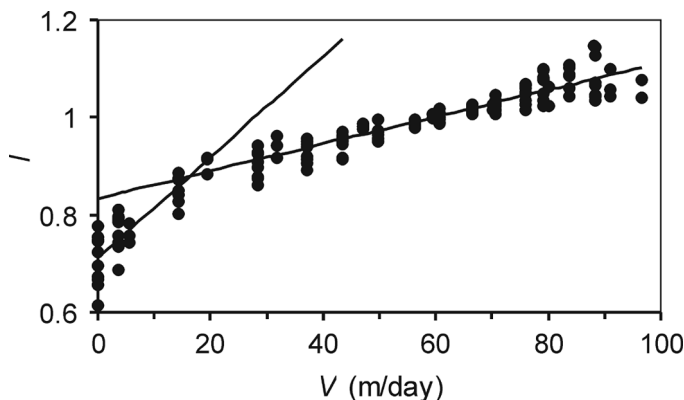


Figure 5. Heater's current against flow velocity for temperature steps between 7.5 and 23.5°C for 160 experimental points with the probe in contact with saturated sand. The results are normalized to the value of the current for flow velocity 59 m/day for every temperature step.

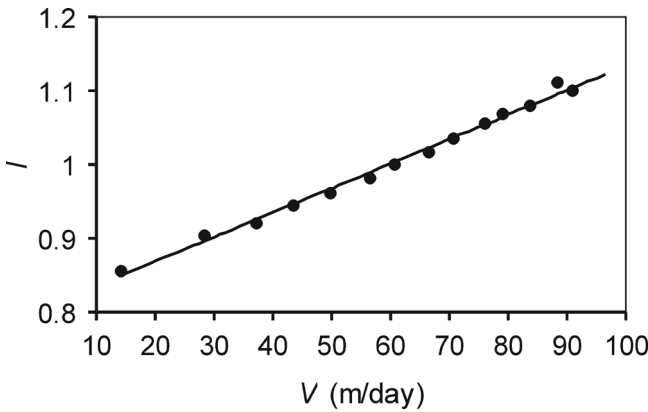


Figure 6. Average curve from five tests in which the temperature step ranged between 6.6 and 7.75°C. The results are normalized to the value of the current for flow velocity 59 m/day for every temperature step.

velocity was approximately linear in the range 15–100 m/day. The screen was then placed such that one of its columns without slots faced the water flow. It was found that the transference was not monotonic. It follows that when a standard 2-inch screen is used, the transference depends on the angle of incidence of the flow, so it would not be possible to know the magnitude of flow velocity within these standard screens. Using screens with more slotted columns or coiled wire screens could perhaps allow the magnitude of flow velocity to be estimated.

The RDP Within a 4-Inch Screen

In this case it was possible to estimate the magnitude of flow velocity regardless of the direction of flow velocity with respect to the slotted columns, because with a 4-inch screen water always finds enough slotted area facing the flow. The tests were conducted with the maximum and minimum slotted area of the screen facing the flow, and it was found that although dispersion increases with respect to that found for a 2-inch screen, there is an increasing function between heater’s current I and flow velocity V . Two of the tests are shown in Fig. 7, in which the current increment, ΔI , needed to keep the heater’s temperature constant is plotted against flow velocity. It is likely that dispersion increases because water flow becomes more turbulent within the largest diameter screen. The transference could be fitted by a straight line for flow velocities less than 100 m/day, which is the maximum stable and repetitive velocity generated in the test apparatus. It was not possible to test the RDP for higher velocities where the transference seems to flatten.

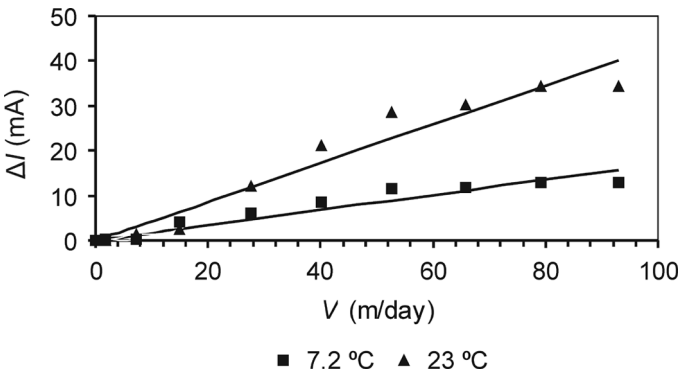


Figure 7. Increment in the heater’s current against flow velocity for the probe inside a 4-inch screen for temperature steps of 7.2 and 23.4°C. The transference is fitted by a straight line for flow velocities less than 100 m/day.

Foam-Rubber Filling

An attempt was made to prevent the RDP from being in direct contact with the water within the 4-inch screen. This was achieved by filling the whole screen with a 17 cm long foam-rubber filling. Some results are shown in Fig. 8 for two temperature steps: 11.9 and 14.8°C. The linear fitting is good, and the dispersion, reasonable. The maximum differences with respect to the linear fitting are less than ± 5 m/day. The foam-rubber porous medium improved the sensitivity of the RDP and lowered the dispersion.

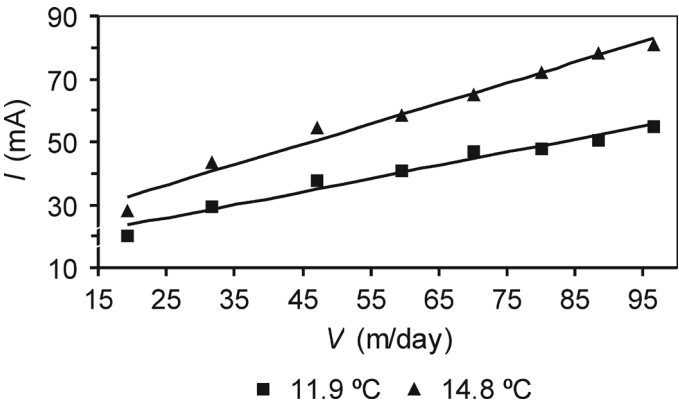


Figure 8. Heater’s current against flow velocity for the probe inside a 4-inch screen with a foam-rubber filling for two temperature steps: 11.9 and 14.8°C.

The calculated transference slopes for temperature steps of 12°C for the RDP surrounded by water, foam-rubber and saturated sand were 0.29, 0.42 and 0.99 mA day/m, respectively. The greatest sensitivity was thus obtained with the RDP in saturated sand.

Direction of Flow Velocity

Excitation with constant power pulses produces differential temperature pulses between opposite thermistors that die away and vanish in a short time interval. Instead, excitation with constant temperature steps produces temperature differences between opposite thermistors that remain stable, and ensures that even at high flow velocities there is a measurable temperature downstream of the heater. Thus, a possibility for determining the flow direction is to rotate slowly the sensor head of the RDP until the direction of the maximum temperature difference between opposite thermistor is found.

The RDP in Contact with Saturated Sand

Figure 9 shows an example of the tests with the RDP in direct contact with saturated sand for flow velocity 37 m/day and a complete rotation. As expected, the maximum temperature difference ΔT between the two opposite thermistors of a sensor axis is obtained when the flow is parallel to the sensor axis. Starting from a maximum, the response is strong for the first 10°, but becomes unnoticeable for angles greater than 40°.

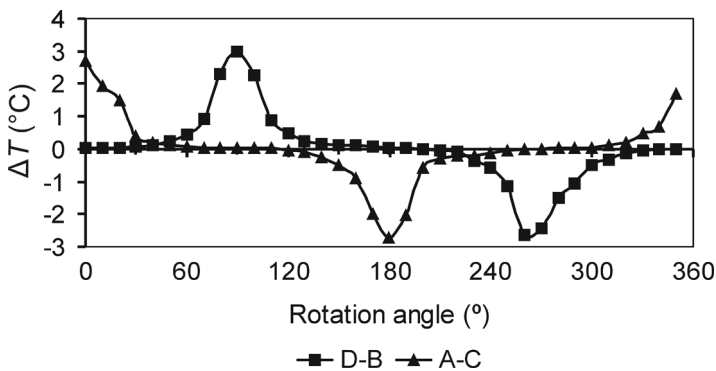


Figure 9. Temperature difference between the two opposite thermistors of sensor axes A-C and B-D (see Fig. 4) with the probe in contact with saturated sand and flow velocity 37 m/day.

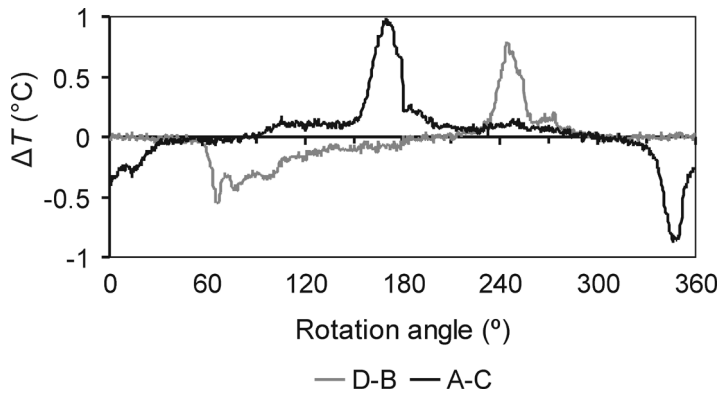


Figure 10. Temperature difference between the two opposite thermistors of sensor axes A-C and B-D (see Fig. 4) with the probe inside a 4-inch screen and flow velocity 50 m/day.

The RDP Inside Screens

If the peaks were always well defined, water flow direction could be obtained with just only one thermistor separated from the heater. However, the presence of irregular peaks, such as those depicted in Fig. 10 for flow velocity 50 m/day, makes that option quite unrealistic. Then, the use of a probe with four temperature sensors seems a more reliable solution.

The angular distance between the peaks from a given pair of opposite thermistors was approximately 180°. This is correct and indicates that the

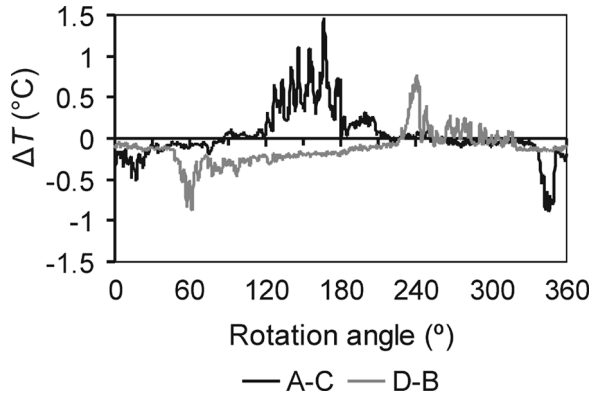


Figure 11. Temperature difference between the two opposite thermistors of sensor axes A-C and B-D (see Fig. 4) with the probe inside a 4-inch screen and flow velocity 100 m/day.

RDP had no manufacturing asymmetries. If the screen had no influence on the RDP response there would be temperature peaks at 0, 90, 180 and 270°, as seen in most cases. However, there are some records that do not strictly show this behavior (Fig. 10). This effect may be due to a setting of the RDP not concentric with the screen axis, and also to a not constant angular velocity of the RDP. At the highest velocities attained with this apparatus (100 m/day) the pulse loses sharpness, probably because of turbulence within the screen (Fig. 11).

DISCUSSION

Magnitude of Flow Velocity

The new RDP has a transference curve with a bend at approximately 15 m/day (Fig. 5). This is because heat propagation at low velocities is mainly diffusive, whereas at high velocities it is mostly convective.

This RDP allows the magnitude of flow velocity to be estimated within boreholes with standard 4-inch screens. Within standard 2-inch screens the method is sensitive to the direction of flow velocity with respect to the slotted columns of the screen, but it is thought that if a coiled wire screen were used, or if the number of slotted columns were increased, it would be possible to measure within these 2-inch screens as well. The highest sensitivity is obtained with the RDP in direct contact with the saturated porous medium. Within the screens the sensitivity decreases, and an increasing dispersion affects the estimation of flow velocity. The use of a foam-rubber filling between the RDP and the screen increases the sensitivity and decreases dispersion. Better results would perhaps be obtained by using a foam-rubber with a lower and more homogeneous porosity.

Flow Direction

As in other thermal probes,^[5,8] the angular response is not of a cosine type, so vector addition for obtaining flow velocity, as suggested elsewhere,^[4,9] is thus not recommended.

A way of measuring the flow direction can be derived from the fact that the location of the temperature peaks from one sensor axis coincide with the location of null temperature difference from the other (orthogonal) sensor axis (Figs. 9, 10, and 11). This condition was used to generate a series with four peaks composed of the records from both sensor axes. To find the angle formed by the flow direction and one of the sensor axis (arbitrarily chosen), the experimental series was correlated with a

theoretical one with peaks at 0, 90, 180, and 270°. The results from 24 tests for flow velocities between 5 and 100 m/day threw a mean squared error of 1.3° with respect to the actual direction, and the standard deviation was 0.9°.

Other investigators^[10] have studied the accuracy in determining flow direction with three different instruments under field conditions, and found that on many occasions the differences in flow direction obtained from successive measurements with the same instrument were on the order of 45°. The laboratory results obtained with the RDP are clearly better than those obtained by these investigators,^[10] but a field working instrument has to be built and tested in a borehole to know if this advantage remains under similar conditions.

Technological Features

It had been assumed from the model that the relation between flow velocity and the power delivered to the heater could be fitted reasonably well by a linear regression. The tests showed that the relation was not as linear as expected. The power delivered to the heater was smaller than the calculated one. On the other hand, the relation between the heater's current and the flow velocity had a more linear character.

In studying the possible reasons for the above-mentioned discrepancies, it was recognized that the model did not take into account the resin cover of the heater because the need for such a cover came from constructing requirements subsequent to numerical analysis. It was found

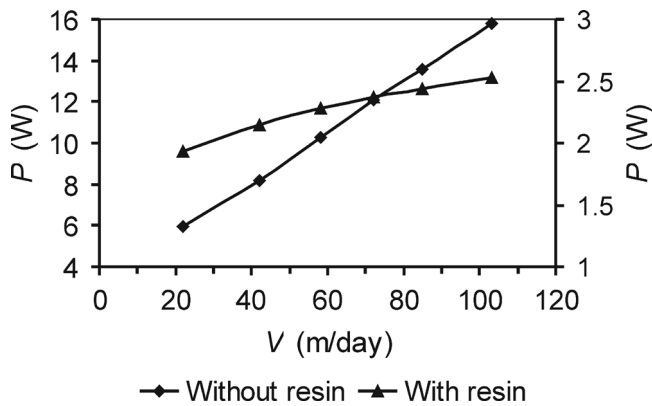


Figure 12. Model results of the power delivered to the heater as a function of flow velocity for the heater with and without a 1 mm thick resin cover of thermal conductivity 0.1 W/m °C and a temperature step of 13°C. The ordinate axis on the right corresponds to the resin-covered heater.

that the thermal conductivity of resins similar to that used in the tests were an order of magnitude less than that of the saturated porous medium. Thus, the heater did not behave as an ideal heat source of constant temperature, as was tacitly assumed in the model, because the thermal resistance of the resin was in series with the heater. The model was then modified to include a 1 mm thick resin layer around the heater. The thermal conductivity of the resin was $0.1 \text{ W/m}^\circ\text{C}$. The results from the model with and without the resin layer are shown in Fig. 12 for a temperature step of 13°C . It is seen that just only 1 mm of resin have greatly influenced the theoretical RDP behavior. Decreases in the amount of power P delivered to the heater and in the linearity of the transference were confirmed by the modified model. However, some differences still remain between measured and calculated results.

CONCLUSIONS

A new probe for measuring groundwater flow was developed and tested, both in direct contact with saturated sand and within standard plastic screens. The numerical simulations of the probe suggest that it should work properly with flow velocities up to about 1000 m/day, even though it was tested only with flow velocities up to 100 m/day. With this new probe it is possible to determine flow direction by means of rotary movement in a porous medium and within screens. The construction of a heater with a very low thermal resistance could improve the experimental results. Also, for new designs, it is convenient to use a stepping motor synchronized with the acquisition of the temperature samples, and some mechanical device to assure that the probe rotates on the screen axis. Although the results shown in this work were obtained under laboratory conditions, the method appears to be promissory for field work.

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