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# A TOOL AND A METHOD FOR OBTAINING HYDROLOGIC FLOW VELOCITY MEASUREMENTS IN GEOTHERMAL RESERVOIRS

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## ABSTRACT

Downhole instruments based on a thermal perturbation principle are being developed to measure heat flow in permeable formations where convective transport of heat is important. To make heat flow measurements in these regions, the ground water velocity vector must be determined. A downhole probe has been designed to measure the local ground water velocity vector. The probe is a cylindrical heat source operated at a constant heat flux. In a convecting environment, surface temperatures on the probe are perturbed from those values of a purely conductive environment. With the aid of analytical and numerical models, these temperature differences can be related to the local velocity vector.

## INTRODUCTION

Hot wire or hot film anemometry is commonly used in engineering applications to determine flow velocities of gases in pipes, channels and other configurations. A simple hot wire anemometer measures the velocity of a gas indirectly by relating the power supplied to the sensor to the velocity of the fluid in a direction normal to the sensor (Dally et al, 1984). Heat produced by ohmic dissipation within the sensor element is removed by the flow of cooler gas past the element. The resultant cooling of the element causes a change in its electrical resistance that can be related to the fluid velocity. We describe here a tool based on a similar approach that can be used to estimate flow velocity in a permeable medium. It is found that application of the hot wire approach is relatively uncomplicated if the tool is placed in a permeable formation so that the porous matrix surrounding it is left more or less undisturbed. This circumstance could be achieved for a shallow well drilled into a sandy zone with backfilling of the hole. Calculations indicate that the tool can also be used in the wire-line mode in an uncased hole if the effects of the well pressure distribution on the pressure field in the porous medium are considered.

## ANALYSIS OF OPERATION

A three dimensional analytical model for flow in a permeable medium past a heated prolate spheroidal body has been developed by Romero (1983a). The geometry of the problem solved by Romero is illustrated in Figure 1. Here a slender body of radius, a, and length, 2l, is aligned parallel to the vertical axis, z. The azimuthal coordinate of the Darcy velocity is given by $\phi$ while its angle to the vertical is given by $\theta_0$. The dimensionless quantity $\eta$, which defines the axial location on the probe, is scaled by the half length, l.

In a saturated porous medium, Darcy's law and the Boussinesq approximation are assumed to apply. For a given velocity $U_\infty$, which characterizes Darcy flow in the far field of the tool, a solution for the pressure and temperature fields in the vicinity of the heated tool was obtained. In particular, the solution for the temperature distribution on the tool surface as a function of both the far field velocity and prescribed heat flux across the tool surface is required. There are two significantly different length scales that characterize the problem. One is the characteristic dimension of the tool while the other is the thermal diffusion length, $\alpha/U_\infty$, where $\alpha$ is the thermal diffusivity. The ratio of the two lengths is given by the Peclet number Pe. The typical difference in length scales (Pe<<1) necessitates matching between an inner region near the tool and an outer region to obtain a perturbation solution. Details of the mathematical analysis can be found in Romero (1983a) who obtains a general solution for the problem valid for Pe <1. The resulting equation for the temperature, T, on the surface of the probe is

$$\frac{-T + T_\infty}{Q\ a/k} = T_o + \frac{\pi}{8}\ Pe + Pe\ Cos\theta_o\ g(\eta)$$

$$+ \frac{a}{l}\ Pe\ sin\theta_o\ cos\phi\ h(\eta) - \frac{a}{l}\ Ra\ f(\eta) \quad (1)$$

Temperature is a function of the heat flux, Q; the conduction solution, $T_o(\eta)$; the Peclet number,

$$Pe = \frac{Ul}{\alpha}$$

the Rayleigh number,

$$Ra = \frac{\rho_o g \beta K Q l^2}{k \alpha \mu}$$

and the functions $f(\eta)$, $g(\eta)$ and $h(\eta)$ that are plotted in Figure 2. We point out that the Rayleigh number used here is a measure of the convection induced in a region of permeability, K, subject to gravitational acceleration, g, by local buoyancy associated with the heat flux from the probe and the volumetric thermal expansion, $\beta$ . Ideally this effect should be small allowing the term involving the Rayleigh number to be neglected compared to terms containing the Peclet number. For most field conditions that have been encountered this has indeed been the case. If Ra is comparable to Pe, then it is apparent from the equation that terms associated with forced convection, i. e., terms involving Pe, can be masked by the term involving Ra that includes the effect of natural convection induced by the probe heater. When the flow is entirely vertical, i. e., parallel to the probe axis, manipulation of the above equation for surface temperature yields the following result for the temperature difference between two locations that are symmetrical about the mid line:

$$\frac{-T(\eta) + T(-\eta)}{Qa/k} = Pe[g(\eta) - g(-\eta)] - Ra\ \frac{a}{l}[f(\eta) - f(-\eta)] \quad (2)$$

This result indicates that the temperature difference between the two locations is linearly related to the flow velocity through the nondimensional Peclet number. A similar result was also obtained by Romero (1983b)for purely vertical flow using a slender body analysis that applies for all values of the Peclet number. For small values of this parameter it is found to be in good agreement with the perturbation result. However, at larger values (Pe> 1), the temperature change becomes smaller for a given change in velocity, i. e., the tool becomes less sensitive at higher Darcy flow rates. We will further consider this equation as well as the more general one (1) in conjunction with laboratory and field tests of a full size convective flow probe. The theory for the convective flow probe has also been tested using bench scale laboratory experiments that were particularly well controlled. These help to illustrate the role of the induced convection in affecting the sensitivity of the probe to groundwater flows.

## BENCH SCALE EXPERIMENTS

In the scaled down laboratory experiments and analysis of Hickox, Dunn and Gartling (1985), the geometry of the probe model was essentially that assumed for the theoretical model in Figure 1. A typical probe model consists of a long (aspect ratio 20), chromel wire wrapped rod (10 cm heated length) with at least two thermistors located at different positions along its electrically heated length. In the absence of any flow in the surrounding permeable medium, the axial temperature distribution is symmetric about the midpoint of the heated length. When there is flow in the permeable medium, the temperature distribution is skewed along the heated length of the model. Thus a temperature difference will be measured between the symmetrically positioned thermistors. This difference can be related to the magnitude and direction of flow using Equation 1.

A 61 cm long plexiglass cylinder filled with sand contained the probe which was embedded parallel to the centerline. For this case the porosity and permeability were .35 and 16 darcies, respectively. A vertical upward flow was produced in the cylinder by maintaining a constant pressure difference across the bed. The observed relation between measured temperature difference and axial flow velocity is plotted in Figure 3 using the dimensionless quantities $\Delta\Theta$ and Pe where the former quantity is given by $\Delta\Theta = 2\Delta T \alpha l / Q$ . For a given heat output, Hickox et al. found a more or less linear change in the temperature difference for a change in axial flow velocity just as predicted by Romero for small Pe. Further, they found that the sensitivity (slope) was greatest for Peclet numbers less than 1. Beyond this value, increases in velocity result in much smaller increases in the temperature difference. This result is consistent with the slender body analysis of Romero.

## FULL SCALE LABORATORY TESTS

A prototype wire line tool was developed for carrying out both full scale laboratory and down hole tests. The tool is shown in Figure 4. Because of the additional features required for wire line operation, the probe is significantly more complicated mechanically than the simple probes used in the bench scale experiments. The tool's overall length is approximately 2 m. and its diameter is about 5.7 cm when the heater and sensor pads are in the fully retracted position. The frame and most of the components of the tool are machined from 304 stainless steel. A dc motor mounted in the tool sets the compression packers as well as driving a scissors mechanism that extends the segmented cylindrical heater and sensor pads until they contact the borehole wall. The current tool can function in wells up to 3 inches (7.7 cm) in diameter. The four laminated silcon rubber heating/sensing pads are the heart of the tool. A thin strip heater runs the full length (56 cm) along the base (tool side) of each pad. In addition, four calibrated thermistors, symmetriclly arranged in a diamond pattern, are positioned above the heating element near the top side (borehole wall side) of each pad. In principle, at least three thermistors are necessary for determining a velocity unambiguously. However, sixteen are used to improve resolution of the velocity vector and to provide redundancy in measurements. For shallow holes (short cable lengths) it was considered adequate to make only two wire thermistor measurements especially since the characteristic resistance of the thermistors was several hundred thousand ohms. Periodic heater wattage and thermistor resistance measurements were obtained and recorded using a Hewlett Packard data acquisition system that included a portable HP 85 computer.

For testing and calibration, the probe was embedded in a 1.2 m diameter tank filled with sand. Water was pumped at a uniform rate through a plenum in the base of the tank. Flow up the cylindrical tank was extracted at the top and returned to the pump reservoir. Temperature measurements at various locations in the tank were made using calibrated thermocouples embedded in the sand. Typical pumping rates of about a liter per hour yielded Darcy velocities of about $2 \times 10^{-7}$ m/s or roughly 8 m/yr. Three pumping rates were used during the test corresponding to a low value of .89 l/hr, a medium value of 1.39 l/hr and a high rate of 1.9 l/hr. Three power levels were also used during the series of tests. Values of 32, 62 and 126 watts are characteristic of power levels that would be used in downhole environments. While higher heater power levels permit larger temperature differences to be measured and, hence, smaller flow rates, an upper limit is imposed on heating rate both by the tendency to induce natural convective flow and by the possibility of exceeding the boiling point of the groundwater. The predicted linear relationship between temperature difference and flow velocity was generally suported by the results as indicated in Figure 5.

## NUMERICAL SIMULATION OF FLOW AROUND PROBE IN WELL

Because the probes are buried in the porous medium in both the bench scale and full size experiments, the analysis of Romero applies directly. However, if the tool is used in a borehole, some modification of the analysis is necessary. For general usage, it is found that the more or less hydrostatic pressure distribution in a borehole will significantly affect flows in the vicinity of the tool. In an uncased hole, the hydrostatic pressure distribution on the borehole wall requires that the vertical component of flow vanish in the porous medium at the wall.

Figure 6a illustrates how the pressure distribution would be modified in the vicinity of an uncased hole. Below the hole, isobars are horizontal indicating vertical flow. Near the hole, however, the isobars are severely distorted and become vertical giving rise to a purely radial flow at the borehole wall. (Obviously continuity does not permit fluid to flow into or out of the hole everywhere if fluid is not being removed or added to the well. A change in sign of the radial component of flow must occur at some depth although it is not shown here.)

A tool such as the convective flow probe will further modify the near field pressure distribution. Along the portion of the hole containing the tool, the flow through boundary condition will no longer apply. Fluid is prevented from flowing radially into the hole and must flow along the tool. If either by design or error, small quantities of borehole fluid can be communicated past or through the tool causing the hole to remain in hydrostatic equilibrium, then a bidirectional flow along the probe will be set up as shown in Figure 6b. For a short (1 m) probe, the induced bidirectional flow is found to be virtually symmetric near the tool independent of the direction of the vertical flow in the far field. Longer probes (5 m) give rise to asymmetry in the bidirectional flow that is associated with the direction of the far field flow. It would also appear that the probe's sensitivity to the azimuthal direction of the flow improves with increasing length of the packed off region.

## FIELD TESTS--LONG VALLEY, CA.

The full scale probe was field tested in two drill holes in Long Valley Caldera, CA. The holes were located near existing USGS heat flow holes where temperature profile data had been obtained. The Sandia hole SLV1 is in a region of suspected upflow while hole SLV2 is in a region of suspected horizontal flow. During the tests electrical leakage problems developed in two of the four instrument pads. While the heater function was not inhibited in these pads, accurate measurement of the temperature was prevented. However, the eight thermistors in the other two pads provided quite sufficient information for estimating the fluid velocity vectors. Before placement of the probe in a drill hole, caliper logs were run to determine uniformity of the side walls as well as the depth to the uncased portion of the hole. A depth interval having the most uniform hole diameter was then selected. After the tool was lowered to this depth, the internal motor was operated to extend the heater pads against the borehole wall and the isolation packers were set. The probe was then allowed to equilibrate thermally in the holes for two hours. The heaters were then powered and data were recorded as a function of time using the computer controlled data acquisition system. Power levels used in SLV1 were 137 and 215 W. After steady state was achieved a vertical temperature difference of about 4 C, related to the upward component of groundwater flow, was measured. Using a modified slender body analysis valid for higher Pe than the original perturbation analysis of Romero, a very large upward velocity of $U=2.4 \times 10^{-5}$ m/s (760 m/yr) was estimated. Using a similar procedure in SLV2, a velocity vector of magnitude $6.8 \times 10^{-7}$ m/s oriented at 79° to the vertical was obtained. The influence of the borehole in the SLV2 flow measurements was fortuitously minimized by packing off one end of the probe in the well casing while the pads extended beyond into the uncased part of the hole.

## CONCLUSION

From the results presented here, we conclude that hot probe anemometry provides a realistic approach to estimating Darcy velocities in a permeable regime. Probes which are embedded in a permeable medium can produce data that is readily modeled using the theory of Romero (1983a,b). However, if a probe is used in a borehole, the effect of the hydrostatic pressure distribution in the borehole on the measured velocity vector becomes a factor. However, numerical calculations indicate that substantially lengthening the probe will minimize this effect. Preliminary field tests of the probe have yielded results which appear consistent with the geothermal settings of the wells.

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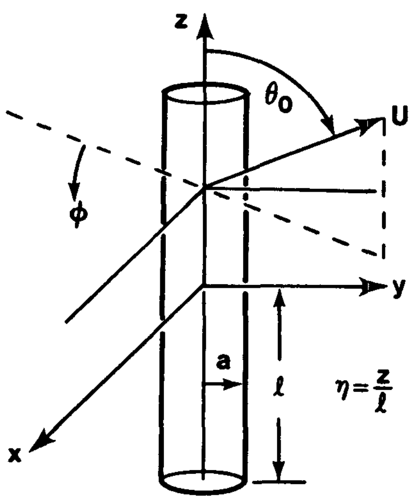


Figure 1. Heated cylinder is embedded in porous matrix. Darcy flow vector is expressed in cylindrical coordinates.

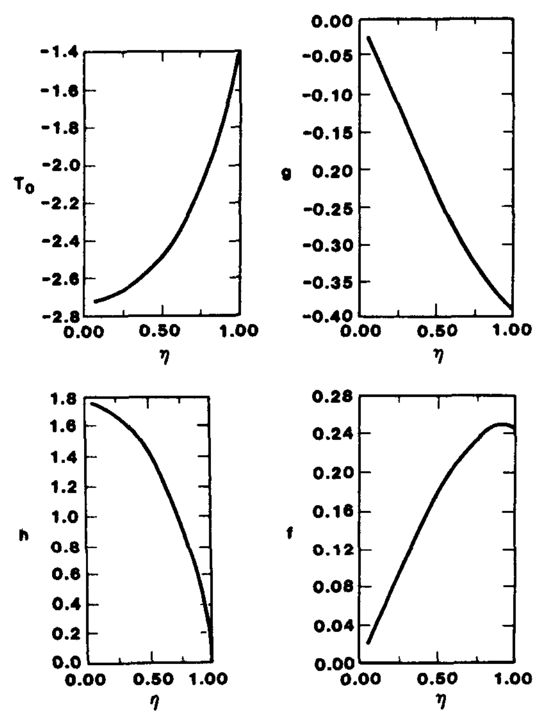


Figure 2. Plots of nondimensional functions and conductive temperature solution appearing in Equation 1.

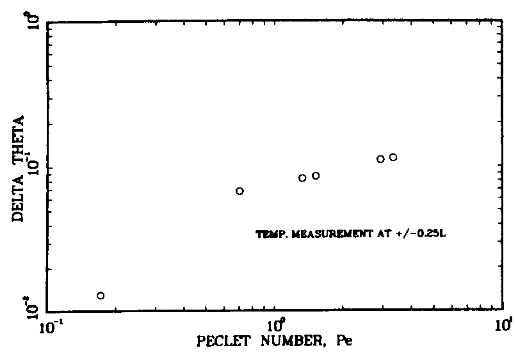


Figure 3. Relationship between temperature difference and flow velocity as expressed by Peclet number. Result obtained from bench-scale experiments.

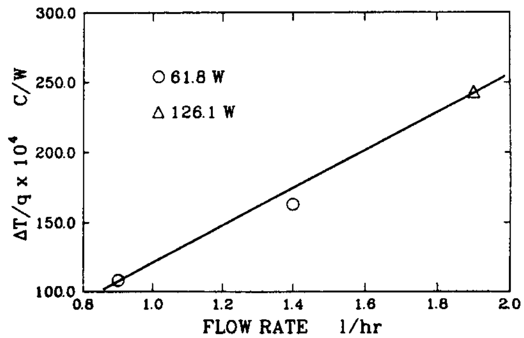


Figure 5. Linear relationship between temperature difference measured at points symmetric about midline and flow rate is supported by full scale laboratory tests.

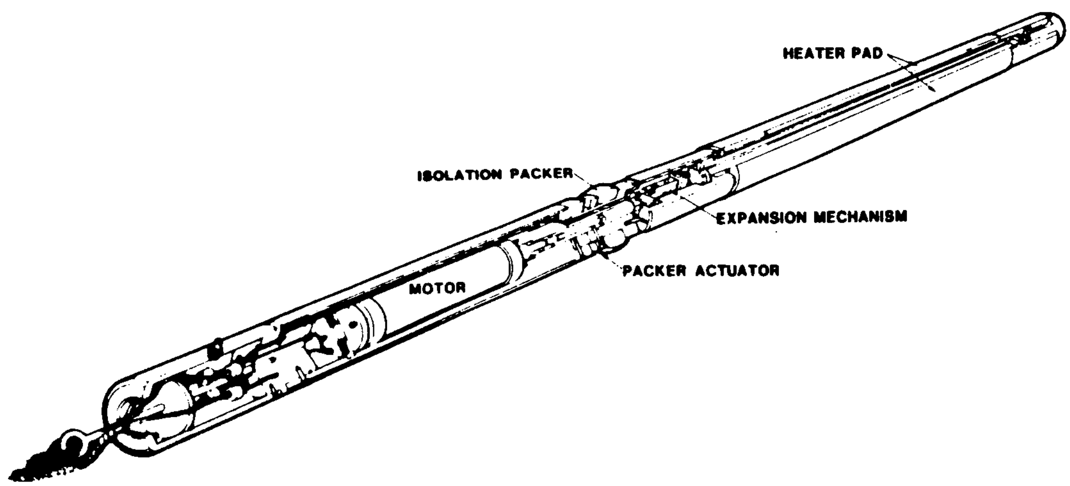


Figure 4. Full size probe design suitable for downhole usage.

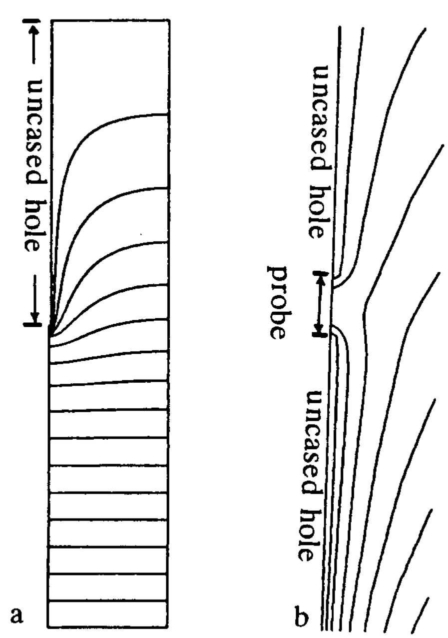


Figure 6. a) Far field isobars are strongly affected by hydrostatic pressure distribution in uncased well. Horizontal isobars give rise to vertical flow. Near well isobars become vertical resulting in radial flow. b) For short tool in uncased well, more or less symmetric isobar pattern implies existence of bidirectional flow.