Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

A New, Small, Wireless Instrument to Determine Ground Thermal Conductivity In-Situ for Borehole Heat Exchanger Design

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Keywords: wireless temperature logging, borehole heat exchanger, thermal conductivity profile

ABSTRACT

A small, light, wireless borehole probe has been developed and built which consists of pressure and temperature sensors and a mini-datalogger/programmed microprocessor in a closed metal tube, water-tight up to 100 bar. The probe (235mm long, 23mm dia, 99.8 g) sinks in completed but not yet working borehole heat exchangers (BHEs) through its own weight to the bottom of the BHE U-tube and records pressure (=depth) and temperature at pre-selected time intervals during descent. After completion of the logging the probe is flushed back to the surface by a small pump where the probe is connected to a laptop computer for data retrieval. The measurement run for a 300 m deep BHE takes less than 60 minutes. The wireless temperature logging has numerous advantages over cable-type logging. Our instrument has a temperature resolution of ± 0.003 °C.

In the data processing the λ profile of the logged BHE is calculated, with a regional heat flow value at hand, from the temperature gradient along the BHE to be derived from the measured temperature log. Besides thermal conductivity determinations for the design of BHE arrays there are numerous other applications for the wireless probe: 1) lithological subdivision of the borehole profile, 2) data base for paleoclimatic studies, 3) identification of groundwater flow.

1. INTRODUCTION

Borehole heat exchangers (BHE), coupled with heat pumps are nowadays increasingly applied for space heating and cooling. The heat exchange between the BHE and the surrounding ground depends directly from ground thermal conductivity λ at the site in question. λ is thus a key parameter in designing borehole heat exchanger (BHE)-coupled geothermal heat pump systems: the specific heat extraction rate (W per meter BHE length) is directly proportional to λ (see Table 1) and the temperature difference between the circulated fluid and the undisturbed ground temperature. This must be considered especially in the design of BHE groups: optimization of the BHE group by determining the BHE number and depth must be implemented immediately after receiving the λ information.

Although λ can be determined on rock samples from the borehole in the laboratory or in-situ by a customary "Response Test" (a BHE circulation experiment), both methods need special equipment and are time-consuming. Therefore we developed a new, simple technique for rapid λ determinations: a wireless probe is lowered into one tube of the U-shaped BHE where it sinks under its adjustable weight and records pressure (=depth) and temperature while going down. After the probe has reached the U-tube bottom it stops there and then it is flushed back to the surface by a small pump for recovery and data retrieval. From the measured temperature-depth profile and the local heat flow value the λ profile around the BHE in question can be calculated.

2. PROBE CONSTRUCTION

A small, light, wireless borehole probe has been developed and built which consists of pressure and temperature sensors and a mini-datalogger/programmed microprocessor in a closed metal tube, water-tight up to 100 bar.

The probe itself has a length of 235 mm, a diameter of 23 mm and weighs only 99.8 g. Figure 1 shows the probe before assembling. For widespread application, several probes have been built.

The key components of the built-in probe electronics are the analog/digital converter, the microprocessor and the EEPROMs (=electric erasable/programmable read-only memory) for data storage (Figure 2). All components have been selected after careful evaluation. For example, an A/D converter with 16bit resolution has been chosen.

Table 1: Rock thermal properties and their influence on BHE performance

Rock type	Thermal conductivity ($Wm^{-1}K^{-1}$)	Specific extraction rate (W per m)	Energy yield ($kWh\ m^{-1}\ a^{-1}$)
Hard rock	3.0	max. 70	100 - 120
Unconsolidated rock, saturated	2.0	45 - 50	90
Unconsolidated rock, dry	1.5	max. 25	50

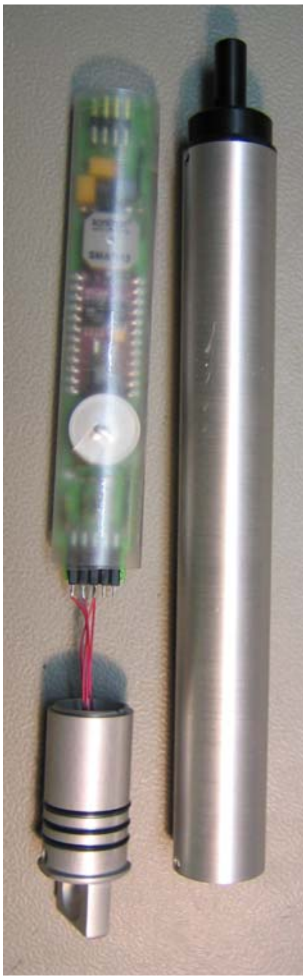

Figure 1: Sensor, electronic board and casing of the probe.

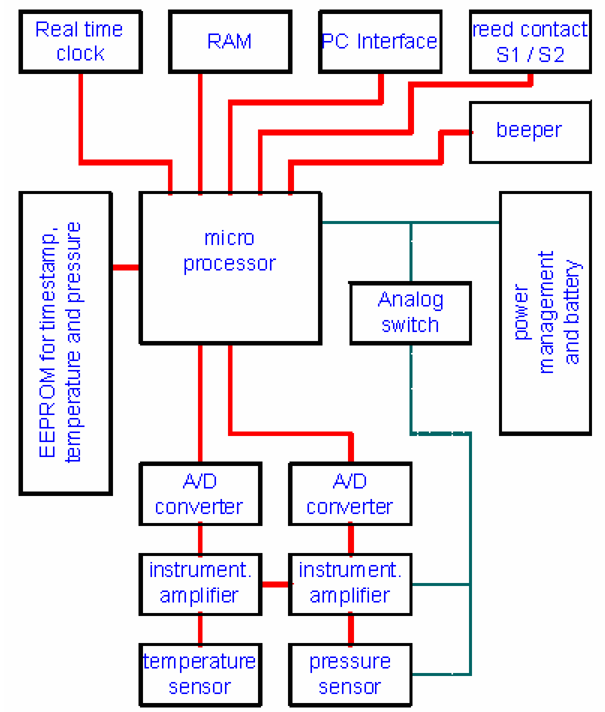

Figure 2: Block diagram of the probe.

3. SOFTWARE FOR OPERATION AND DATA RETRIEVAL

The software consists of three parts to perform the following tasks:

1) Controlling the probe operation

2) Communication probe – laptop computer (for data retrieval)

3) Calibration

The controlling part runs in a programmable microprocessor (Basic Stamp BS2pe), performs the measurements and stores the data (time, pressure, temperature).

The communications part consists of a macro in an Excel Workbook, reads the data into an Excel table and enables the configuration of the wireless probe. It also enables to set the measurement mode as well as the setting of time, pressure and temperature intervals. Data deletion as well as synchronization of probe and laptop timing is also accomplished.

Also the calibration part consists of a macro in an Excel Workbook; it enables to calibrate individual probes. The calibration parameters are stored in the probe. Thus the measurements can immediately be started, after configuration, with any of the probes built.

4. LABORATORY TESTS AND CALIBRATION

Function checks (after testing the water-tightness up to 100 bar) have been performed under laboratory conditions. The temperature calibration was done in a thermostat vessel, the pressure calibration by hydraulic means. The probe has high temperature resolution (± 0.003 °C) and can store three times 16’000 measurements (time, pressure, temperature). The time constant of temperature measurement is 3.5 sec. Depth resolution is, due to the time constant, about ± 0.5 m.

The calibration functions for pressure and temperature are described by second grade polynoms of the form $y= a + bx + cx^2$. The calibrations constants a, b and c of each individual probe are stored in the probes.

5. MEASUREMENTS

The measurements consist of field measurements of temperature-depth profiles by the wireless probe in selected BHEs on one hand, and of laboratory measurement of thermal conductivities on cuttings from the same boreholes on the other.

5.1 Field measurements

Before measurement, the probe used is configured to start data acquisition. The weight of the probe is adjusted by small weights mounted in the closed tube to achieve the requested logging speed (on the order of m/min). The time interval for data acquisition and storage is also set. After the probe has reached the bottom of the BHE it is retrieved and attached to a laptop computer for data readout. Figure 3 (left) shows a typical measured temperature-depth profile, along with the geologic profile of the BHE drillhole. A 300 m deep BHE can be measured in less than 60 minutes.

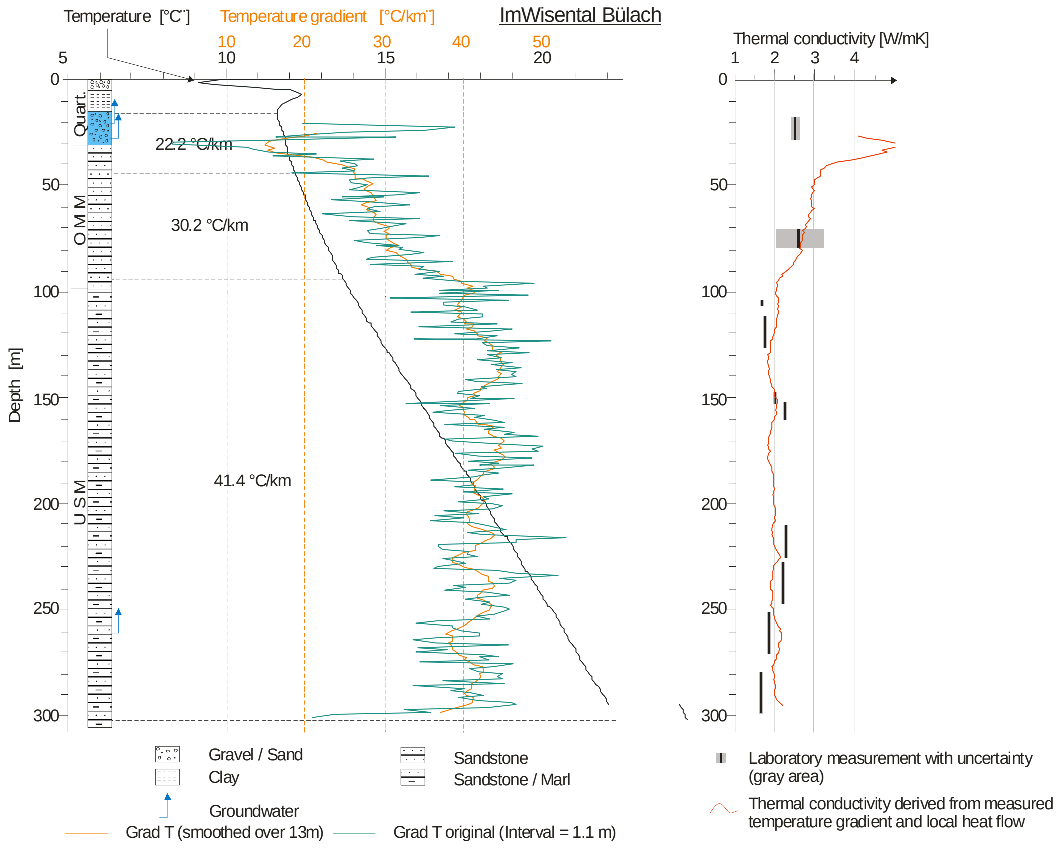

Figure 3: BHE borehole Im Wiesental, Bülach near Zurich. Left: geologic column, measured temperatures (with gradient sections; black line), gradient calculated with the original measurement spacing of Δz=1.1 m (blue line) and smoothed over Δz=13 m). Right: calculated thermal conductivity profile (brown line) with laboratory results (black bars).

Table 2: Petrophysical data, measured on samples from the BHE borehole Im Wiesental, Bülach near Zurich.

Probe	Depth	Lithology	λ_m [W/m,K]	$\Delta\lambda_m$ [W/m,K]	ρ_m [g/cm^3]	ϕ_{eff}	$\Delta\phi_{eff}$	λ_f [W/m,K]	$\Delta\lambda_f$ [W/m,K]
IW-1	5 - 18 m	Clay						1.69	0.05
IW-2	18 - 28 m	Gravel	3.55	0.18	2.69	0.20	0.05	2.50	0.11
W-1	72 - 80 m	Middle-/Coarse-sandstone	2.89	0.07	2.48	0.20	0.05	2.12	0.06
W-2	104 - 106 m	Marl	2.19	0.09	2.34	0.20	0.04	1.70	0.02
IW-3	112 - 126 m	Marl/Fine-sandstone	2.17	0.09	2.48	0.17	0.02	1.74	0.01
W-3	148 - 152 m	Fine-sandstone/Marl	2.37	0.20	2.59	0.15	0.01	1.95	0.03
IW-4	150 - 160 m	Fine-sandstone/Marl	2.64	0.07	2.53	0.12	0.02	2.23	0.02
IW-5	210 - 226 m	Fine-sandstone/Marl	2.69	0.20	2.57	0.13	0.01	2.22	0.03
IW-6	228 - 248 m	Middle-sandstone/Marl	2.62	0.14	2.57	0.13	0.01	2.17	0.02
W-4	252 - 272 m	Marl/Siltstone	2.20	0.07	2.55	0.16	0.01	1.79	0.01
IW-7	278 - 298 m	Marl	2.07	0.15	2.46	0.17	0.02	1.69	0.02

λ_m: thermal conductivity of matrix, ρ_m: density of matrix, Φ_{eff}: effective porosity, λ_f: thermal conductivity of water-saturated sample, Δ: measurement error

5.2 Laboratory measurements

For validation of the thermal conductivity profile calculated (details see below), laboratory measurements on cutting samples from the same boreholes have been performed. The equipment as well as the measurement method is described in detail in Schärli and Rybach (2001).

Table 2 displays the results of such measurements from an investigated BHE drillhole at the site "Im Wisental" in Bülach near Zurich.

6. CALCULATION OF THERMAL CONDUCTIVITIES FROM THE WIRELESS PROBE MEASUREMENTS

The thermal conductivity calculation is based on pure conduction. Therefore, disturbing effects like the influence of ground temperature changes (due to paleoclimatic variations), groundwater flow effects must be eliminated from the measured values beforehand. From the measured temperature profile the local geothermal gradient is then calculated layerwise (1st derivative; ∇T_i: temperature gradient of depth section i)

$$\nabla T_i = \frac{T_u - T_1}{z_u - z_1} \quad (1)$$

where T_u is the temperature measured at the top ($z = z_u$) and T_l at the bottom ($z = z_l$) of interval i.

Finally, with the local terrestrial heat flow value qloc (obtainable from regional heat flow maps; e.g. Medici and Rybach 1995), the thermal conductivity of each individual depth section can be calculated:

$$\lambda_i = \frac{q_{loc}}{\nabla T_i} \quad (2)$$

7. RESULTS AND DISCUSSION

The kind of results obtainable by the wireless probe is presented in Figure 3. On the left side, the temperature profile is displayed (black line) along with the profile of the temperature gradient. The latter is given by a blue line (original data with a constant Δz of 1.1 m and by a brown line (smoothed; gliding average over Δz = 13 m).

The right side of Figure 3 displays the thermal conductivity profile as calculated by eq. (2). For comparison, the results of laboratory measurements of thermal conductivity are also given (black vertical bars). The agreement is remarkably good; thus the method of calculating the thermal conductivity profile from the temperature profile measured by the wireless probe yields highly reliable, in-situ thermal conductivities.

8. CONCLUSIONS AND OUTLOOK

Since the development and field testing of the new wireless probe in 2003 numerous BHE's have been measured in Switzerland. The individual results are all fully satisfactory. Now the method is routinely used for the design of larger BHE arrays.

The wireless measurement also offers advantages over temperature logging performed by cable-mounted probes: higher resolution, very high signal/noise ratio.

Often the so-called Response Test method (fluid circulation in a BHE with subsequent outflow and inflow temperature measurements) is used for in-situ thermal conductivity determinations (see e.g Sanner 2001). It provides a mean value of thermal conductivity, averaged over the entire borehole length. The wireless method described above yields the detailed thermal conductivity profile. A further, significant advantage: a 300 m deep BHE can be measured by the wireless probe in less than 60 minutes whereas a reliable Response Test needs at least 50 hours of fluid circulation time (Mands et al. 2001). The time saving under field (construction site) conditions is highly relevant.

Besides thermal conductivity determinations there are numerous other applications for the wireless probe: 1) Lithological subdivision of the borehole profile, 2) data base for paleoclimatic studies, 3) identification of groundwater flow.

ACKNOWLEDGMENTS

The dedicated efforts of Ralph Baumgartner (formerly with GEOWATT AG) in designing, construction and testing the wireless probe are gratefully acknowledged. Great thanks are due to Harald Gorhan and Markus Geissmann (Swiss Federal Office of Energy, SFOE) for continuous encouragement. The design, construction and testing phase was financially supported by the SFOE (Project no. 47'947).

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