A temperature logging system: Development and Application

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Abstract

Temperature logging equipment made in Brazil, for continuous geothermal measurement is presented. Digital and analog circuits and a temperature probe with an interchangeable negative temperature coefficient (NTC) thermistor were developed. The probe and electronic circuits are linked by a long three wire lead that makes feasible to compensate the cable effect on measured values. Cable is turned in a winch at surface where electronics circuits are fixed. Coupled to temperature sensor through cable there is a 22 bits resolution ADC delta-sigma converter MCP3551 that is controlled by a fast 16 bit digital signal processor (DSP) PIC30F3012 microcontroller. After 10 measurements in every probe position, a mean value is calculated and it can be visualized in an external LCD alpha numeric display. The probe depth value is given by a sheaver made with a small magnet fixed in a pulley. Two stable Hall magnetic sensors make possible a depth resolution of 10 cm. The measured depth values are displayed in a commercial handheld calculator directly in meters. Preliminary probe calibration curve for resistance versus temperature was determined in laboratory by using the ultra stabilized thermostatic bath HAAKE MK22. The best fit of each pair R-T was gotten with accuracy of ± 0,02°C, following the Steinhart and Hart equation. Ground water movements generate characteristic anomalies on geothermal gradients. Therefore some temperature anomalies related to ground water moving through fractured rocks can be detected at surface. Then a temperature logger is very useful to study the influence of ground water movements mainly when associated with seismicity occurring in some localities of São Paulo State. It was the main motivation for developing the present temperature logging system.

Introduction

Geothermal measurements are very much useful for detecting a wide range of information mainly when the geothermal method is associated to other well logging ones. Rock fractures, water movements and changes on lithology all of them generate thermal gradients variations or anomalies. However this searching method is not so applied to geophysics purposes in Brazilian territory. One of the reasons is because for logging a well it must be without the pumping system and such condition is not easy to find at the place and time we need to.

The cost for enough good and precise equipment is another difficulty. Therefore the present temperature logging system totally developed in Brazil makes it very much attractive because of its low cost but much more because it will give the opportunity for important field works including classes on Geophysics graduation courses. The results from a preliminary application showed a quite good agreement when compared to the measurements obtained in the same well using another thermal logger. The temperature logging system presented here is not the first Brazilian thermal logger, however, this is the first one that can read digital and almost continuously both the resistance and the correspondent depth. The probe is quite stable therefore the measurements are very easy and quickly taken.

The usually available electrical wire-line (cable) apparatus for temperature measurement can be divided into four subsystems: the probe with temperature sensor, the multi wire cable, the sheaver and the data acquisition systems in surface.

The earlier types of bulk semiconductor resistance temperature sensors used in accuracy geothermal gradient measurements were made of manganese, nickel, and cobalt oxides. These oxides were milled, mixed in proper proportions with binders, pressed into the desired shape, and sintered. After encapsulated, these ceramics semiconductors devices were named by thermistor, which main characteristic are to have a very large negative temperature coefficient.

Replacing the Wheatstone bridge as the surface instrument, recently accurate and inexpensive digital voltmeters or analog to digital converters with microcontroller are becoming available. In order to obtain 0.01°C resolution, a 4½ digit meter is necessary and a 5½ -digit meter will allow a resolution of 0.001°C (Blackwell & Spafford, 1987).

In order to link the probe inside the well with the acquisition equipment at surface a three-lead cable is typically used Therefore the effect of cable resistance variations due water temperature and probe-cable weights can easily be compensated. Silver graphite on coin silver slip rings is usually used to connect the cable conductors to the surface measurement system.

However, with recent improvements in the technology, it is possible a continuous bore hole logging and so getting accurate temperatures measurements with less than a few thousandths of a degree (mK). This means that temperature gradients can be determined precisely, to within about 0.2°C.km^{-1}(mK.m^{-1}) over distance of about a meter.

In practice, temperature logs can be used in a number of ways. Many physical properties are temperature dependent, and temperature data are used to reduce other logs to a common temperature reference level. When cement is used to shore a collapsed section of a hole or to set casing in place, it is possible to check the position of the cement by lowering a temperature probe which responds to the heat of reaction of the setting cement.

Temperature measurement apparatus

The developed temperature measurement logger (Figure 1) has four subsystems as described in various terrestrial heat flow works:
a) the probe with thermistor as temperature sensor,
b) three wireline cable and winch,
c) sheaver to get the probe depth,
d) acquisition equipment in surface

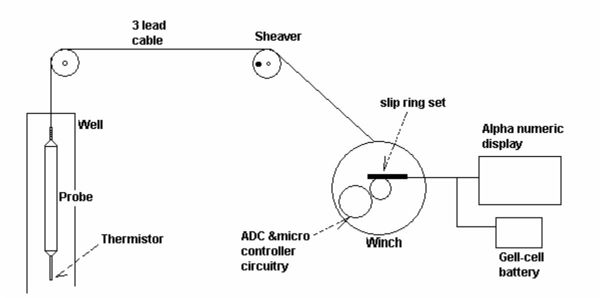

Figure1-The wireline apparatus for temperature measurement in depth wells.

Temperature Probe Characteristics

The temperature logging probe is a 30 mm diameter copper tube with 30 cm length. At one edge of probe there is a small diameter (5 mm) tube where the NTC thermistor EPCOS (interchangeable B5786 serie) is fixed with silicone grease. One lead ballast is placed into the probe to avoid that it floats in proportion that it descends into the hole.

The probe is sealed by means of o' ring, and silicone rubber is used to fill the probe inside to avoid water input.

The sensor is connected to the surface via electrical conductors, and a quasi- continuous recording of resistance versus well depth is obtained.

If the hydraulic regime is almost static, the probe response time in water-filled holes is about 15 s.

Description of temperature sensor and calibration curve

A NTC thermistor is a sensor composed of semiconductor material which has a steep negative temperature versus resistance curve (Robertson et al. 1966). Generally its resistance-temperature relation is given by:

$$R = R_o \; e^{\beta\left({}^{1}\!/_{T} + {}^{t}\!/_{T_o} \right)} \quad (1)$$

where:
R - resistance at temperature T, Ώ
R$_o$ - resistance at temperature T$_o$, Ώ
β - constant, characteristic of material, K
T, T$_o$ – absolute temperatures, K

The reference temperature T$_o$ is generally taken as 298 K (25^o C) while the constant β is of the order of 4,000. Then the temperature coefficient of resistance is given by:

$$\left(dR/dT \right)/R = -\beta/T^2 \quad (2)$$

If β is taken as 4,000, the value of this parameter at room temperature (25^o C) is -0.045.

Commonly thermistors are available in the form of beads, and because their strong exponential behavior with temperature, we need to calibrate in laboratory using ultra-stable thermostatic bath. Then resistance values versus temperature can be adjusted by the best fitting curve, using PC program.

When using precision interchangeable thermistor, we generally will have a degree-by-degree chart of resistance versus temperature furnished in the manufacturer's data. Sometimes, however, it is handy to have a precise equation when using a computer to convert the thermistor's resistance to temperature. Except for very narrow temperature spans, the single-term exponential is not good enough: more terms are needed.

The best approximation in common use today is known as the Steinhart and Hart equation:

$$\frac{1}{T} = a + b \ln R + c \left(\ln R \right)^3 \quad (3)$$

where:
T- absolute temperature (in degrees Kelvin)
R- thermistor's resistance
a, b and c – experimentally determined constants

Equation 3 generally agrees with the actual thermistor to within a few thousandths of a degree over spans as wide 1000^{o}C. Of course, it can be that good only if the experimental thermistor data is equally accurate. Temperatures accurate to thousandths of a degree can be provided only in top- grade laboratories.

Constants a, b and c are found by solving three simultaneous equations obtained by substituting three pairs of known R, T points (at the low, middle and high ends of the desired range) provided by manufacturer or determined in laboratory, into the Steinhart and Hart equation. For ranges of 100^o C or less, curve-fit accuracy is within about ± 0.02^o C (Doebelin, 1983). Manufacturer's generally do not provide specified values of a, b and c, since they vary depending on the temperature range.

The best fit to the experimental measurement of NTC resistance at different temperatures over the range 15 to 40^o C is obtained by using following equation, (Katz. and Shaughnessy,1988):

$$T = \frac{1}{\exp\left\{ a + b\left(\ln R_T\right) + c\left(\ln R_T\right)^2 + d\left(\ln R_T\right)^3 \right\}} \quad (4)$$

The residuals in the least- square fitting process were often at the expected level of uncertainty in the temperature measurements, about 0.02^o C.

In calibration procedure, the probe curve resistance versus temperature was determined in laboratory by using ultra stabilized thermostatic bath HAAKE MK22, whose temperature was accurately measured by a PT1000 resistance and 4 ½-digit voltmeter. Then, the best fit of each pair R-T was got with accuracy of ± 0, 02 ^{o} C, using Steinhart and Hart equation.

Interchangeable thermistors have proved to be extremely stable and in some case, NTC sensors have drift less than 0.001^{o} C in the past 19 years (Roy et al., 1968).

Response times of NTC sensors mounted in thin-wall stainless steel hypodermic tubing in water-filled holes are a few seconds. In air, 10-20 minutes may be required for a measurement (Blackwell and Spafford, 1987).

The depth control

The probe depth is determined by a sheaver where the electrical cable slips on a pulley with 20 cm length (Figure 1). A small magnet is fixed on it and two Hall magneto-sensors are fixed near this pulley. For every pulley turn, two digital pulses are generated by Hall sensors that trigger an 8 digit handheld calculator. For every pulse, modified calculator adds 10 cm, and we have depth measurement directly in meters. This procedure is carried out in ascent as much as in the descending movement of the probe inside the well, with great reproducibility.

The multi-wire cable

Typically, a three-lead cable is used to link the probe into the well with acquisition equipment in surface. Then the effect of cable resistance variations due water temperature and probe-cable weights can be easily compensated. In usual analog compensation mode, the silver graphite on coin silver slip rings are usually used to connect the cable conductors wounded up around the winch to 41/2 digit DVM.

In the first prototype, we use slip rings with 3 (graphite brushes- copper coin) sets. Contact resistance was about 10Ω that was high for our purpose.

To avoid the electrical resistance of slip-ring (or mechanical contact) the electronic measurement circuit (ADC and microcontroller) was placed together the winch. Leads from cable are coupled directly to acquisition system input (Figure 2). Then, the mechanical contacts are used to transfer digital data from microcontroller to an external alphanumeric LCD display.

Electronic configuration and algorithm to determine the probe electrical resistance

The ratio-metric technique is used to resistance determination of NTC thermistor inside the geothermal probe and to remove the multi-wire cable interference.

The electronic circuit

The ADC delta-sigma converter MCP3551 has 22 bits resolution, and for every depth it makes 10 measurements and the average value is transferred to an external display by parallel bus through 3 graphite brushes-copper coin sets (slip rings). This set allows voltage bias of all electronic circuits fixed in the winch body, too. By the way, any error introduced in the NTC resistance measurement is nullified, because all information are transferred in digital mode. In the first prototype where analog mode of transfer was adopted, error due brushes and copper collectors set was about 10 Ω. Analog CMOS switches CD4066 controlled by fast 16 bits digital signal processor (DSP) PIC30F3012 microcontroller allowed fast sequential measurements of NTC resistance and of wire-line cable in ratio-metric configuration. After arithmetic operations made by PIC microcontroller, it was possible to read directly the corrected value of NTC with high accuracy. The time constant of probe is about 15 seconds and after it, lectures of NTC value become very stable and fluctuation are lower than 1 ohm. Response time upper than this value, possibly indicates water movement associated with input or leakage of water into or from the well hole. When the response time is upper this value, possibly there are water movement associated with input or exit of water into the well hole.

The acquisition system was built on ADC MCP3551, with 22 bits resolution that agrees with a 6 digits DVM. This integrated circuit has two rejection notch filters centered in 50 and 60 Hz that allows low output noise of 2.5 μV_{RMS} with 22 bits resolution. The maximum sampling rate is 14 SPS (samples per second).

In the schematic diagram (Figure 1), the voltage reference V_{REF} of the 22 bits ADC converter (MCP3551) is applied to current limiting resistor R_o (20 kΩ± 0.1%) . Accuracy of this metal- film component is about 0.1% and drift is lower than 1ppm/^{o}C. These parameters become essential when we are going to get 0.02^{o}C resolution.

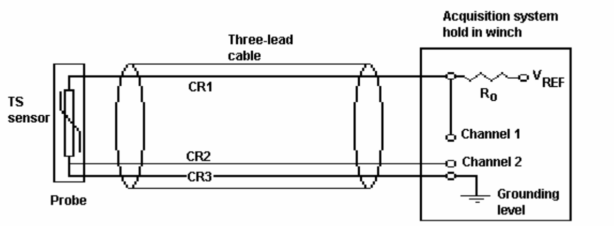

Figure 2- Schematic diagram of electrical wireline apparatus for temperature measurement.

In fact the true 22 bits ADC allows resolution in order of 0.001^{o}C, but much more stabilized power source and best electrical and mechanical components would be necessary and this project would become very expensive.

The resistance values of the three- wire cable linking sensor TS to the probe with acquisition system at surface are represented by CR1, CR2 and CR3.

The electrical current due V_{REF} flows through R_o, TS and CR3 only, because currents in Channels 1&2 are disregarded due high input impedance of ADC converter (2.4 MΩ). The voltage in Channel 1&2 outputs are taken relative to ground level in CR3. Then, we have these known parameters: a) voltage reference V_{REF} and b) current limiting resistor R_o.

The voltage measurements are:

a) V_1 in Channel 1 input, that is voltage serial drops across CR3, TS and CR1,

b) V_2 in Channel 2 input, that is drop voltage on CR3 only, because current across CR2 is about zero. These two voltages (V_1 and V_2) are measured sequentially by using of analog switches provided with CMOS 4066 CI, controlled by PIC microcontroller.

After 10 voltage determinations by each channel, microcontroller takes the meaning values and by algebraic calculations described below, determines only the resistance of NTC, already discounted the cable value, with precision better than 1Ω .

Algorithm Structure

The resistive temperature sensor TS is directly connected to the delta-sigma ADC and a single low tolerance resistor is used to bias the TS from the ADC reference voltage. This configuration named ratio-metric allows accurate resistance measurements. A linear regulator is used to provide a reference voltage. This voltage is used to bias the TS and ADC which provides a ratio-metric relation between the ADC and the TS resolution.

The key feature of a ratio-metric measurement technique is that temperature accuracy does not depend on the accurate voltage reference (Halle, 2008)**.**

The ADC voltage input has always positive values, and then the full-scale will be 2^{21} for V_{REF}. Therefore the current across TS will be:

$$I = \left(2^{21} - V_1\right) / R_o \quad (5)$$

The sum of voltages in the V_{REF} loop will be:

$$V_{REF} = V_{R_o} + V_{CR1} + V_{TS} + V_{CR3} \quad (6)$$

where: V_{TS} – sensor voltage .

As $V_{CR1} = V_{CR3}$ and $V_{CR3} = V_2$, and by Eq.6:

$$V_{REF} - V_{R_o} = V_1 = V_{TS} + 2V_2 \quad (7)$$

Then

$$V_{TS} = V_1 - 2V_2 \quad (8)$$

Dividing both sides of Eq. 8 by I given in Eq. 5:

$$R_{TS} = R_o \left(V_1 - 2V_2\right) / \left(2^{21} - V_1\right) \quad (9)$$

The current crossing temperature sensor TS doesn't need be constant, but must have low value, in order of µA, to doesn't heat the sensor by Joule effect.

In the ratio-metric configuration, stability and accuracy don't depend of V_{REF} stability, and V_1 and V_2 can be written as V_{REF} percentage:

$$V_1 = aV_{REF} \quad \text{and} \quad V_2 = bV_{REF}$$

Where *a* and *b* are constants.

Substituting in Eq. 5:

$$R_{TS} = R_o \left(a - 2b\right) / \left(2^{21} - a\right) \quad (10)$$

Equation10 shows that accuracy of R_{TS} (temperature sensor) is related to V_1 and V_2 fluctuations during sequential measurements and to R_o precision.

Results

The entry and exit points of water inside a well can be found from a temperature log T versus z or, for easier visibility, the derived temperature gradient log ($\partial T / \partial z$) versus z. In a case of perturbation to the temperature-depth and gradient- depth plots due to water entering the hole from a horizontal permeable bed and exiting at lower level, the shape of curve depends on the flow rate.

Influence of a down-hole water flow on the temperature- depth and gradient- depth regime are noted inside the two wells (Figs 3&4). If the down-hole water flow is high, temperature T becomes almost constant with depth, in the interval between input and exit of water into the borehole (Beck,1965).

Advection or forced convection is a very efficiency form of transferring heat; if in an otherwise undisturbed region the hydraulic regime is such that water starts to flow along a hole when it is drilled, perhaps connecting two previously unconnected aquifers, the conductive regime is easily perturbed and even small flows can be readly detected by thermal methods (Beck, A.E., 1991). Conduction is a very inefficient form of heat transfer and anything that disturbs it can often be detected quite readily (Beck, 1965).

The thermal regime of the crust is determined largely by the thermal conduction process; this means that in a uniform half-space the T-z log would be linear and with T increasing downward, and the ($\partial T / \partial z$) plot would be constant.

The present temperature logging system was used in the Bebedouro county. In this locality placed at Northeast of Paraná Basin earthquakes are occurring since 2004/2005. This seismicity is related to deep wells drilled for water exploitation from basalt fractures aquifer. All logged wells in that locality present similar thermal behavior (Yamabe et al, 2006). They present almost constant temperature zone followed by a high geothermal gradient layer. The constant temperature zone is caused by a descendent water movement inside the well indicating that water is going out or leaving the well exactly at the top of the high temperature gradient layer. This high thermal gradient zone is just a layer where water inside the hole is receiving heat from surrounding rock so it is getting back to the regional gradient. Therefore by using temperature logging is possible to determine the exact location along the well where the water is coming inside or leaving it.

Comparing with other temperature versus depth curve in steps of two meters got in the same well but in another season (spring), the present acquisition during summer showed very similar general behavior without almost any change (Figure 3). However, a slight rise of temperature (about 0,2°C) was observed probably due to the higher external temperature. The temperature log for this well shows temperature almost constant in the depth interval from 54m to 135m. As one can hear the sound of water falling down inside the well it is possible to say that the water fall is coming from around 36m deep and the water level is at 54m deep. The water leaves the well at around the depth of 135-136m.

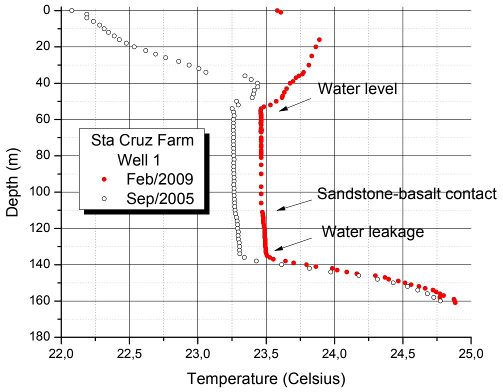

Figure3- Temperature logging in one well located in Santa Cruz farm

The time response of probe used in second profile is about 15 seconds where hydraulic regime is almost static, but at entry and exit points, values are upper than 60 s.

Near surface, diurnal variations from solar disturb are very high and measurements become more unstable. Near bottom of wells, the temperature curve inclination trends to local terrestrial gradient. The approached lithological profile shows that sandstone - basalt contact occurs near 100m deep. The temperature profiles show a slight rise of temperature around depth of 115 meters that can indicate that contact.

In Figure 4 it is shown another temperature profile obtained also using the present equipment. Almost the same temperature behavior is observed. This well is located at Monte Azul Paulista county (Retiro farm), around 30km far from the Santa Cruz farm.

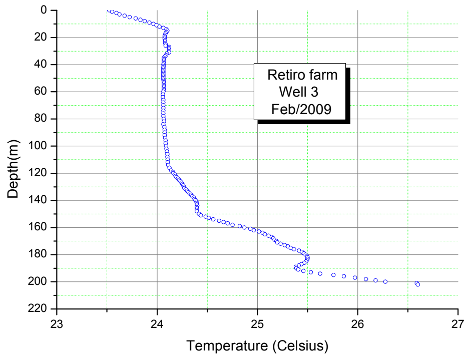

Figure 4-Temperature logging in recent drilled well in Retiro farm.

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Future development

In the new prototype, a portable computer will become possible direct and simultaneous acquisition from ADC converter and sheaver by USB link. Then it will be feasible to visualize the well temperature profile at the notebook monitor.

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References

Beck, A.E., 1965, Techniques of Measuring Heat Flow on Land, in Lee, W.H.K., Ed., Terrestrial Heat Flow :24-57..

Beck, A.E., 1991, Physical Principles of Exploration Methods, Wuerz Publishing Ltd, Winnipeg, Manitoba, Canada.

Blackwell, D.D. and Spafford, R.E., 1987, Experimental Methods in Continental Heat Flow, in Methods of Experimental Physics, Eds: Sammis, C.G. and Henyey, T.L., Academic Press, V24B; pp189-226.

Doebelin, E.O, 1983, Measurements Systems: Application and Design, McGraw-Hill, Inc.

Halle, E., 2008, Precision RTD Instrumentation for Temperature Sensing, MICROCHIP Technology Inc. AN1154.

Hiodo, F.Y., Yamabe, T.H., Ribeiro, F.B. and Galhardo, L.,1997, Perfilagens de Temperatura em Poços Profundos: Instrumentação e Aplicações. In Proceedings of the V Inter. Congr. of Brazilian Geophysical Society,

Katz, I.M and Shaughnessy, E.J.,1988, An electronically switched flowmeter and temperature sensor employing a single thermistor probe. J. Phys. E. Sci. Instrum, 21.

Roy, R.F., Decker, E.R., Blackwell, D.D. and Birch, F., 1968, Heat Flow in the United States. J.Geophys. Res., 73, 5207-5221.

Trietley, H.L., 1985. All About Thermistors. Radio-Electronics, January;P 47-51.

Yamabe, T. H.; Hamza, V. M.; Assumpção, M. & Birelli, C.A. 2006. Movimentos de água subterrânea relacionados com a atividade sísmica em Bebedouro (SP): Inferências com geotermia. II Simpósio Brasileiro de Geofísica. Natal, RN.