Design and Test of an Autonomous Wireless Probe to Measure Temperature Inside Pipes

N. Aranzabal[a], J. Martos[b], A. Montero[c], J. Soret[d], R. García-Olcina[e] and J. Torres[f]

[a] *University of Valencia, Burjassot, Spain, nordin.aranzabal@uv.es*
[b] *University of Valencia, Burjassot, Spain, julio.martos@uv.es*
[c] *Polytechnical University of Valencia, Valencia, Spain, almonter@upvnet.upv.es*
[d] *University of Valencia, Burjassot, Spain, jesus.soret@uv.es*
[e] *University of Valencia, Burjassot, Spain, raimundo.garcia@uv.es*
[f] *University of Valencia, Burjassot, Spain, jose.torres@uv.es*

Abstract:

The BHE length for a given output power depends on the thermal characteristics of the geological layers as moisture, heat transfer coefficients, etc. Measuring the changes in the temperature inside the exchanger pipes can allow an accurate sizing of its length, therefor reducing drilling cost and the payback of the installation.

A miniaturized autonomous wireless sensor, which measures the temperature while is carried by the fluid into the pipes of a geothermal heat exchanger, is used to determine the heat transfer capacity of each of the geological surrounding layers. The developed probe is encapsulated in a sphere of 20 mm of diameter with the same density as the fluid, and thereby is carried at fluid speed. Its features are:

- Temperature range: -10 a 50 ºC
- Accuracy: +- 0.05 ºC
- Sample period: 0.1 – 25 s
- Resolution: <0.05 ºC
- Number of samples: 1000 max.
- Battery less and energy harvesting.

The probe contains an ultra low power microcontroller, a temperature element Pt1000 with a response time of 80 ms, a conditioning circuitry, a non volatile register memory and a RFID device for configuration, data download and sensor supply, all carefully designed in a PCB of 16 mm Ø. An ultra capacitor is charged by RFID in order to power a miniaturized data logger, which can acquire up to 1000 samples.

The objective of this sensor system is to expand the data collected during conventional thermal response test (TRT) and to apply numerical analysis in order to determine the thermal characteristics of the geological structure of subsurface and its influence in the borehole thermal behaviour.

Keywords:

Geothermics, Geothermal Heat Pump, Simulation, Thermal Response Test, Wireless Sensors.

1. Introduction

To achieve the objectives of sustainability, environmental impact reduction and mitigation of climate change, the introduction of cleaner and more efficient energy technologies is essential. For instance, the use of ground source heat pumps (GSHP) or geothermal heat pumps (GHP) as heating ventilation and cooling system (HVAC) to conditioning spaces into buildings and to provide hot water, have a great potential to reduce greenhouse gas (GHG) emissions, energy savings and energy efficiency improvements [1]. A GSHP system can reduce GHG emissions by 66% or more than conventional systems that use fossil fuel, and saving up to 75% of electricity [2].

A great effort has been made to spread the GSHP technology around the world by publishing compilations and reviews which presents the different models and constructive alternatives and their related advantages in energy saving and efficiency [2, 3, 4]. Some experimental facilities have been built with the aim of verifying the energy savings that can be obtained under conditions of normal use [5]. Thus, it has been shown that in temperate climates such as the Mediterranean coast, it can be saved about 43% on heating and 35% on cooling. Moreover, studies of district heating and cooling systems, demonstrate estimable savings in energy consumption in front of individual systems [6].

A key factor in order to increase the dissemination of GHP systems is to reduce the economic cost of Borehole Heat Exchanger (BHE) by an accurate design and sizing. A Response Thermal Test (TRT) was developed in Sweden and the USA in 1995 [7,8] and is currently used for sizing BHEs [9]. These TRT are based on the Infinite Line Kelvin model (ILK) and consist in measure the temperature evolution at input and output points while a constant power heat is injected or extracted into the BHE. Some limitations of these methods are the sensibility in presence of small variations of the heat injection or extraction and that assumes that the subsurface structure is homogeneous. Some works seem to suggest that, in some cases, a significant uncertainty related to the analysis of thermal conductivity for a typical TRT is related with the uncertainty of the heat injection rate. [10]. Moreover, the TRT is affected by other factors such as subsurface disturbance due to drilling and the ambient temperature, so different methods has been proposed to filter these effects [11]. In order to improve the calculus of thermal parameters obtained from the TRT, as subsurface thermal conductivity and borehole thermal resistance, a lot of works has been completed using both, analytical or numerical models [12, 13, 14, 15, 16, 17] and laboratory experiments.

The ILS model assumes that the subsurface structure is homogeneous but that is the exception and not the rule in real GHP installations. To determine the subsurface geological structure, wet and water flows, may be a key factor to optimize power transfer/drilling depth relationship. An improved analysis strategy proposed, focused in reveal the effects of water flows and other possible heat transport processes, involves a multi level power injection [18]. On other hand, several works have explored alternative methods to TRT, introducing new temperature measurement systems along the U-tube using optical fiber temperature sensors or electronic autonomous sensor probes [18, 19, 20, 21, 22, 23, 24].

Furthermore, given the increased power of numerical computer-aided calculations and the introduction of very accurate and reliable simulation programs, a lot of works perform the modeling and simulation of heat transfer applying finite element methods in 2D and 3D models in static or dynamic regime [25, 26, 27, 28, 29]. Since the reduction in computer time is a very interesting factor in order to calculate the thermal parameters and layered structure of subsurface, some works propose to model the BHE by a net of thermal resistance and capacities [30, 31, 32, 33]. This approach shows a good data agreement between finite element models and capacity-resistance models, with a significant reduction in computing time, while allow both dynamic and static analysis. A proper use of these capacity-resistance models to represent real facilities, requires the measurement of the fluid temperature evolution along the pipes during TRT, and only measuring methods as optical fiber thermometer or temperature sensors flowing into pipes [34] can obtain the required input data for using this capacity-resistance model. The main characteristics of the probe described in [34] are:

- Weight: 8 gr
- Diameter: 25 mm
- Temperature range: 0–40 °C
- Resolution temperature: <0.05 °C
- Accuracy temperature: ±0.05 °C
- Sampling interval: 0.1–25 s
- Sampling capacity: 1,000 samples
- Powered by non rechargeable button battery
- Configuration and data download by RF (ISM 868 MHz)

Therefore, it is limited to be used in pipes with a diameter larger than 25 mm, it cannot be employed when the temperature is below 0 ºC, and the useful life is limited by the battery capacity.

Another configurations of heat exchanger used in GSHP, very interesting due to the reduction of costs involved, are those based on pipes embedded in diaphragm wall o piles [35]. For these installations, the conventional TRT offers no guarantee of applicability due to the fact that its geometry does not allow to use the ILK model. Measuring the temperatures inside the tubes as inputs for 3D finite element models or capacity-resistance models may allow to obtain the heat pump system design parameters more accurately. To achieve this goal, autonomous miniaturized sensors may be the most appropriate method to measure the evolution of the temperature inside the tubes while a TRT is completed.

In this paper, a new version of this wireless temperature sensor flowing into the pipes [34] for measuring the thermal fluid during a TRT is presented. It consists of a small sphere (20 mm ø), which contains a programmable temperature acquisition system with wireless RFID power and communication capacities. It can be introduced inside the BHE pipes and flows with the thermal fluid along the whole pipe length while acquiring the fluid temperature. At the output, the sensor downloads all the measured temperature data by a wireless RFID connection to a laptop computer or a tablet.

2. System description

The objective of the sensor is to capture the evolution of the temperature inside the pipes along the BHE. To do so, miniature spherical temperature probes configured to measure the temperature at specified time intervals are introduced by a special valve inside the BHE pipe. The system can be used with standard TRT equipment in order to obtain additional internal temperature data, which allow the detection of the effects of geological layers, wet and water flow on heat transfer.

Figure 1 shows a diagram of the auxiliary elements for sensor insertion (insertion and extraction valves) and its working process. The hydraulic and thermal power generation systems may be those of a TRT equipment. The sensor, which has 20 mm ø and 4 gr of weigh, is carried by the flow at its same speed due to the fact that it has the same density than water. Laboratory tests were performed in order to calculate the positioning error inside the pipe while the flow carried the sensor, obtaining a value smaller than 2% [34].

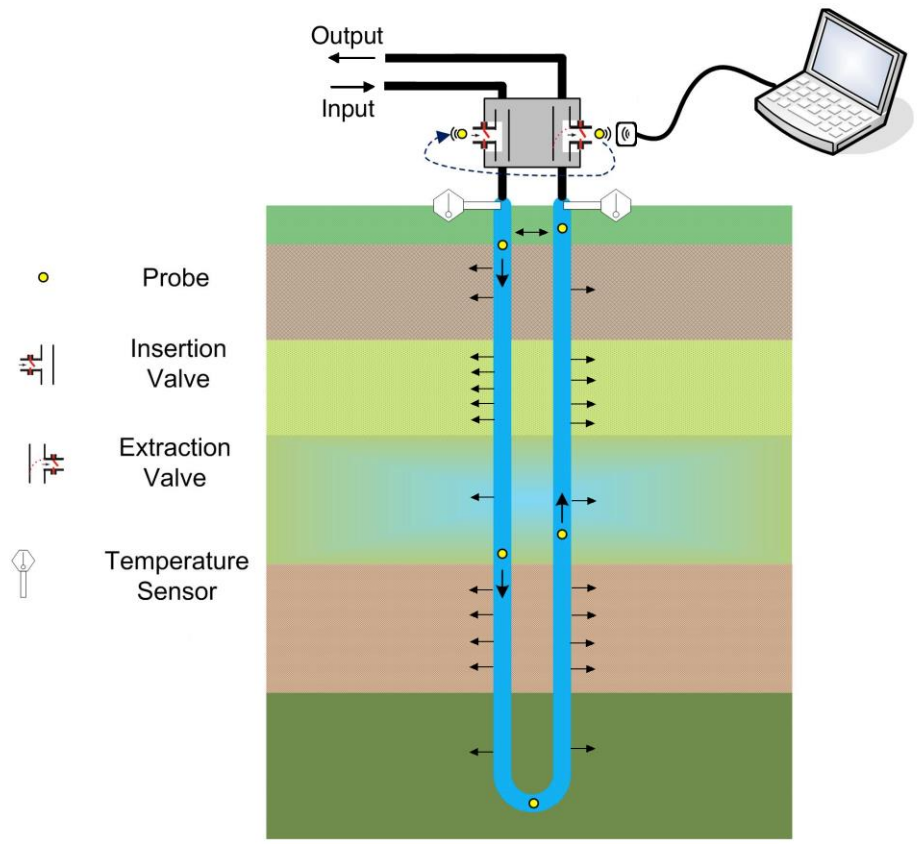

Fig. 1. Diagram of BHE and wireless sensor work.

The operation mode of the sensors is as follows: first, the laptop charges the probe power subsystem by RF induction and waits until a capacitor is full. Then, the parameters of sampling, number of samples and period, are transferred to the sensor by RFID, and the probe is inserted into the BHE water flow by the insertion valve. Automatically the probe starts the process of acquiring and storing water temperature at programmed fixed intervals. Once the travel along the whole BHE pipe is completed, the probe is extracted by means of an extraction valve, the temperature data is downloaded to the control system and the probe goes to low-power mode.

The small size of sensor allows it to be inserted into standard piping installations for BHE, usually 32 mm ø. We can view it as an electronic device that measures, along the pipe, the thermal evolution of an elementary volume of water, that is, how is exchanging the heat with its surroundings. Figure 2 presents an image of the sensor, both encapsulated in a sphere of 20 mm ø and the not-encapsulated circuit, compared with a 1 cent € coin.

All circuitry is disposed on a circular 2 sides printed circuit board (PCB) of 16 mm ø, which includes a 16 bits microcontroller with a 16 bits analog-to-digital converter (ADC) and biasing and conditioning circuit for a temperature sensor Pt1000; a non volatile RFID memory that allow wireless communications and energy harvesting to powered the probe; and an ultra capacitor which stores the energy power needed to temperature acquisition and register process.

The temperature sensor is a planar element Pt1000 class A according to DIN EN 60751, mounted on a ceramic substrate of size 1.6 × 1.2 × 0.4 mm, and response time of 80 ms on water. This sensor type has some interesting characteristics: is inexpensive, drain low power during the measure and doesn't show spatial, temporal and temperature dependence as the optical fiber thermometers. A Wheatstone bridge polarized in voltage is used to energize the Pt1000 temperature sensor in order to obtain a differential signal, which is amplified and digitized by the analogue circuitry of the ultra low power microcontroller.

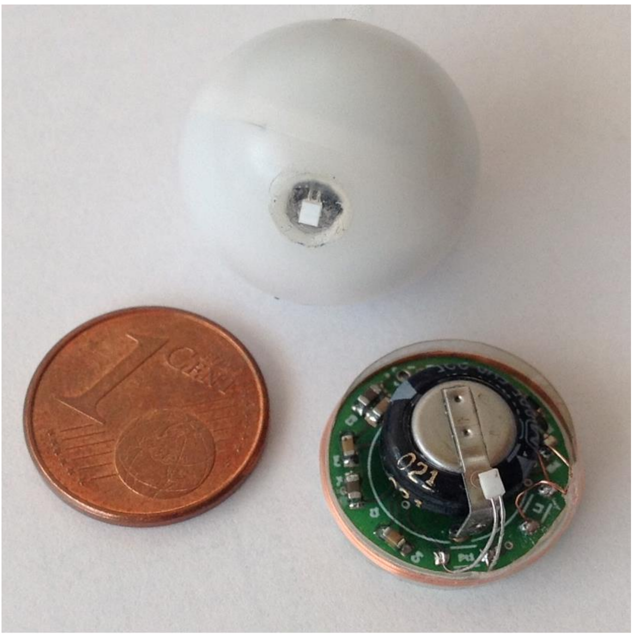

Fig. 2. Electronic circuit of probe and encapsulated sensor.

The characteristics of the autonomous sensor are:

- Temperature range: -10 – 50 °C
- Resolution temperature: <0.05 °C
- Accuracy temperature: ±0.05 °C
- Sampling interval: 0.1–25 s
- Sampling capacity: 1,000 samples

▪ Battery less and energy harvesting

This new probe version shows better characteristics in weight, size, time response, temperature range, supply power system, communication synchronization, and useful life, enabling better usability and applicability in a wide type of buried heat exchangers.

A PC program has been developed using Labview® in order to configure, download, data storage and graphical plotting. The graphical user interface (GUI) is showed in Figure 3. The first step consists in set the values of acquisition parameters: flow, borehole deep, pipe diameter and spatial resolution. From these data is calculated the period and samples number to be acquired and transmitted by RF to the probe, with the start command acquisition, and it is inserted into the U-pipe by a special valve. Then the probe changes to “in acquisition” state, remaining in sleep mode and switches to “acquisition” mode only when the period between samples is reached according with the loaded configuration. After temperature acquisition, the probe saves the data in internal memory, and the microcontroller goes to sleep mode again.

When all planed measurements are completed, the probe changes to “inactive” state, and marks a data set as “acquisition completed”. The PC can access by RF to the data, transfer all the stored data, write in a file and show it graphically.

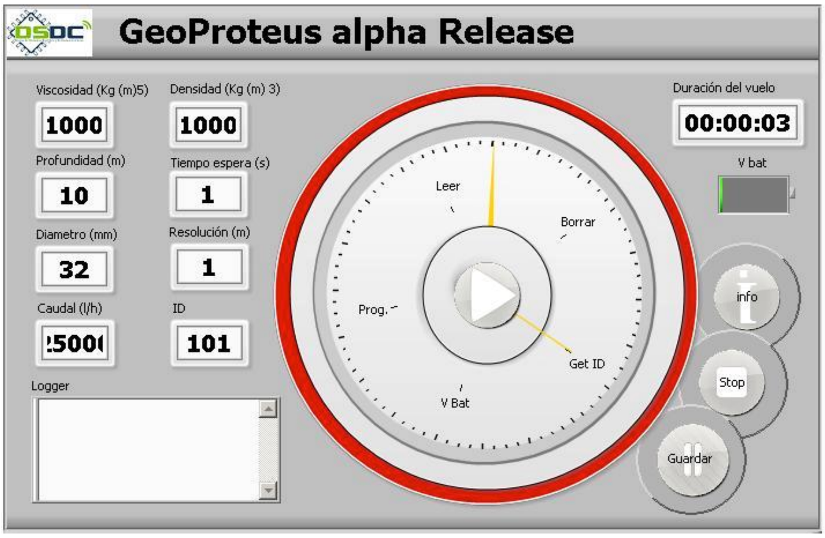

Fig. 3. Graphical User Interface to configure, download, register, and data visualize.

3. Laboratory test

A set of laboratory tests has been completed in order to verify the probe correct operation. First, a study about the level and stability of power voltage vas conducted. In less than ten minutes into a RFID field, the ultra capacitor reaches a voltage of 3.0 volts. In low power mode, the probes maintain enough power during several hours due to the very low current drained by the circuitry.

A clock signal controls the probe tasks, which wake-up the microcontroller when the period of sampler has been accomplished. Acquire a new temperature measure requires only 2 ms of time, and drains 2.04 mA of maximum current. During a laboratory test consisting in acquiring 600 temperature samples at a rate of one per second, the ultra capacitor only reduces its voltage in 300 mV, from 3 V to 2.7 V. Figure 4 show a plot of a acquisition 600 samples in ambient temperature with a second of sampling period without calibration process.

For correct and reliable use, each probe is individually calibrated by means of a thermal bath FRIGITERM 600038 from PSELECTA® and a high precision thermometer P755 from DOSTMANN electronic, in order to obtain the coefficients to linear fit. The user interface has a register of the coefficients of each probe and process the data in order to obtain values with the established resolution and accuracy. Figure 4 presents a screenshot of the graphical window user interface of the calibrated temperatures measured during a test at room temperature.

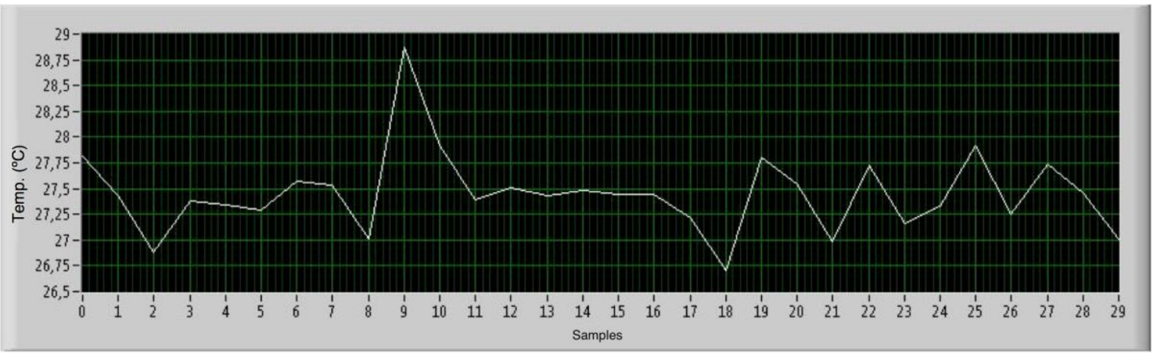

Fig. 4. Graphical print of a probe acquisition.

4. Conclusions

For the expansion of more efficient GSHP systems it is a key factor to develop simpler and more economic methods in both, time and money, regarding BHE sizing. Especially in the case of large BHE systems, new tools and methods for calculating thermal subsurface properties that allow exploit subsurface conditions, such as moisture, groundwater and water flows. The probe and software presented in this work, because of its ease of use and simple integration with standard equipment TRT, provides access to new data that offers the possibility of knowing the surrounding thermal properties, from inside the U-tubes, while performing the TRT.

Furthermore, the probes are properly configured, the data downloaded and the circuitry powered by wireless transmission. The data collected and recorded allows the study and quantification of thermal subsurface effects, such as underground water flows, moisture, *etc*., usually not accessible for conventional TRTs. Additionally, this sensor technology does not use batteries, so its life is virtually infinite.

Finally, this measurement system opens the door to detailed quantitative assessment, not only for vertical BHE configuration, but it can also be very useful for the characterization of other configurations such as diaphragm walls or thermal piles, nowadays in expansion due to the reduction of costs involved.

Acknowledgments

This work was supported by the “VLC/CAMPUS Valencia, International Campus of Excellence” under the program “Valoritza i Transfereix” of Universidad de Valencia 2011 and PhD. Program of Climate-KIC Transforming the Built Environment Platform (TBE).

The sensor system presented in this work is protected by Spanish patent ES 2339735, 21 November 2008.

References

[1] Bayer P., Saner D., Bolay S., Rybach L., Blum P., Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. Renewable and Sustainable Energy Reviews 2012; 16:1256-1267.

[2] Omer A.M., Ground-source heat pump systems and applications. Renewable and Sustainable Energy Reviews 2008; 12:344-371.

[3] Yang H., Cui P., Fang Z., Vertical-borehole ground-coupled heat pumps: A review of models and systems. Applied Energy 2010; 87:16-27.

[4] Lund J.W., Sanner B., Rybach L., Curtis R., Hellström G., Geothermal (ground-source) heat pumps. A World overview. Geo-Heat Centre GHC Bulletin Sept. 2004; 25(3):1-10.

[5] Urchueguía J.F., Zacarés M., Corberán J. M., Montero A., Martos J., Witte H., Comparison between the energy performance of a ground coupled heat pump system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast. Energy Conversion and Management 2008; 49:2917-2923.

[6] Nagota T., Shimoda Y., Mizumo M., Verification of the energy-savings effect of the district heating and cooling system – Simulation of an electrical-driven heat pump system. Energy and Buildings 2008; 40:732-741.

[7] Austin, W.A. Development of an *in situ* System for Measuring Ground Thermal Properties, MSc. Thesis, Oklahoma State University, Norman, OK, USA, 1998.

[8] Gehlin, S. Thermal Response Test–*In-situ* Measurements of Thermal Properties in Hard Rock. Licentiate Thesis, Lulea University of Technology, Lulea, Sweden, October 1998.

[9] Witte, H.; van Gelder, A.J.; Spitler, J.D. *In-situ* measurement of ground thermal conductivity: The dutch perspective. *ASHRAE Trans.* 2002; 108:263-272.

[10] Raymond, J.; Therrien, R.; Gosselin, L.; Lefebvre, R. A review of thermal response test analysis using pumping test concepts. Ground Water 2011; 49(6):932-945.

[11] Bandos T. V., Montero Á., Fernández de Córdoba P., Urchueguía J. F., Improving parameter estimates obtained from thermal response tests: Effect of ambient air temperature variations. Geothermics 2011; 40:136-143.

[12] Beier, R. Vertical temperature profile in ground heat exchanger during *in situ* test. Renewable Energy 2011, 36:1578-1587.

[13] Marcotte D., Pasquier P., On the estimation of thermal resistance in borehole thermal conductivity test. Renewable Energy 2008; 33:2407-2415.

[14] Raymond J., Therrien R., Gosselin L., Borehole temperature evolution during thermal response tests. Geothermics 2011; 40:69-78.

[15] Beier, R.; Smith, M.; Spitler, J. Reference data sets for vertical borehole ground heat exchanger models and thermal response test analysis. Geothermics 2011, 40:79-85.

[16] Bandos, T.; Montero, Á.; Fernández, E.; Santander, J.G.; Isidro, J.; Pérez, J.; Fernández de Córdoba, P.; Urchueguía, J. Finite line-source model for borehole heat exchangers: Effect of vertical temperature variations. Geothermics 2009, 30:263-270.

[17] Reuss, M.; Proell, M. Quality Control of Borehole Heat Exchanger Systems. In Proceedings of the Effstock'09 Conference, Stockholm, Sweden, 14–17 June 2009.

[18] Witte H., Van Gelder A. J., Geothermal response test using controlled multipower level heating and cooling pulses (MPL-HCP): quantifying ground water effects on heat transport a round a borehole heat exchanger. Proceedings Ecostock 2006, Thenth International Conference on Thermal Energy Storage. New Jersey (USA) May 2006.

[19] Hurtig, E.; Ache, B.; Groβwig, S.; Hänsel, K. Fiber Optic Temperature Measurements: A New Approach to Determine the Dynamic Behavior of the Heat Exchanging Medium inside a

Borehole Heat Exchanger. In Proceedings of the TERRASTOCK 2000, 8th International Conference on Thermal Energy Storage Stuttgart, Stuttgart, Germany, 28 August–1 September 2000.

[20] Rohner E., Rybach L., Schärli U., A New, Small, Wireless Instrument to Determine Ground Thermal Conductivity In-Situ for Borehole Heat Exchanger Design. Proceedings World Geothermal Congress 2005, Antalya, Turkey, April 2005.

[21] Fujii H., Okubo H., Nishi K., Itoi R., Ohyama K., Shibata K., An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers. Geothermics 2009; 38:399-406.

[22] Fujii, H.; Okubo, H.; Itoi, R. Thermal response tests using optical fiber thermometers. Geotherm. Resour. Counc. Trans. 2006, 30:545-551.

[23] Acuña, J. Characterization and Temperature Measurement Techniques of Energy Wells for Heat Pumps. M.Sc. Thesis, KTH School of Industrial Engineering and Management Division of Applied Thermodynamic and Refrigeration, Stockholm, Sweden, 2008.

[24] Acuña, J.; Palm, B. A Novel Coaxial Borehole Heat Exchanger: Description and First Distributed Thermal Response Test Measurements. In Proceedings of the World Geothermal Congress, Bali, Indonesia, 25–30 April 2010.

[25] Beier R. A., Transient heat transfer in a U-tube borehole heat exchanger. Applied Thermal Energy 2014; 62:256-266.

[26] Bauer D., Heidemann W., Diersch H.-J. G., Transient 3D analysis of borehole heat exchanger modelling. Geothermics 2011; 40: 250-260.

[27] Corradi C., Schiavi L., Rainieri S., Pagliarini G., Numerical Simulation of the Thermal Response Test Within Comsol Multiphysics® Environment. Proceedings of the COMSOL Conference 2008 Hannover.

[28] Signorelli S., Bassetti S., Pahud D., Hohl T., Numerical evaluation of thermal response tests. Geothermics 2007; 36:141-166.

[29] Raymond J., Lamarche L., Simulation of thermal response tests in a layered subsurface. Applied Energy 2013; 109:293-301.

[30] de Carli M., Tonon M., Zarrella A., Zecchin R., A computational capacity resistance model (CaRM) for vertical ground-coupled heat exchangers. Renewable Energy 2010; 35:1537-1550.

[31] Bauer D., Heidemann W., Müller-Steinhagen H., Diersch H.-J. G., Thermal resistance and capacity models for borehole heat exchangers. International Journal of Energy Research 2011;35:312-320.

[32] Nguyen A., Pasquier P., Marcotte D., Thermal resistance and capacity model for standing column Wells operating under a bleed control. Renewable energy 2015; 76:743-756.

[33] De Rosa M., Ruiz-Calvo F., Corberán J. M., Montagud C., Tagliaficio L. A., Borehole modelling: a comparison between a steady-state model and a novel dynamic model in a real ON/OFF GSHP operation. 32nd UIT (Italian Union of Thermo–fluid-dynamics) Heat Transfer Conference 23–25 June 2014, Pisa, Italy, Publisher: Journal of Physics: Conference Series 547 (2014) 012008, doi:10.1088/1742-6596/547/1/012008.

[34] Martos, J., Montero, Á., Torres, J., Soret, J., Martínez, G., García-Olcina, R., Novel wireless sensor system for dynamic characterization of borehole heat exchangers. Sensors 2011; 11:7082–7094.

[35] Xia C., Sun M., Zhang G., Xiao S., Zou Y., Experimental study on geothermal heat exchangers buried in diaphragm walls. Energy and Buildings 2012; 52:50-55.