SET2010 - 9th International Conference on Sustainable Energy Technologies; Shanghai, China.
24-27 August, 2010

Thermal Response Testing of a Multiple Borehole Ground Heat Exchanger

Saqib Javed[1] **and Per Fahlén**[2]

[1] Building Services Engineering, Chalmers University of Technology,
Gothenburg, Sweden, saqib.javed@chalmers.se

[2] Building Services Engineering, Chalmers University of Technology,
Gothenburg, Sweden, per.fahlen@chalmers.se

ABSTRACT: This paper reports on the thermal response tests performed on the borehole system of a newly developed ground source heat pump test facility. Tests between 48 and 270 hours have been conducted on nine 80 m deep boreholes. Ground thermal conductivity and borehole thermal resistance values have been determined for all nine boreholes using standard evaluation methods. In addition to ground conductivity and borehole resistance values, the undisturbed ground temperatures have also been measured for individual boreholes. A comparison of these three parameters, estimated for nine nearby boreholes, provides useful insight to the accuracy and reproducibility issues of thermal response tests.

Keywords: thermal response test (TRT), borehole, ground heat exchanger (GHE), ground source heat pumps (GSHP).

1. INTRODUCTION

The design of ground source heat pump (GSHP) and borehole thermal energy storage (BTES) systems requires accurate knowledge of properties like ground thermal conductivity, borehole thermal resistance and undisturbed ground temperature. For medium to large sized systems, these properties are often determined using an in-situ thermal response test (TRT) of a pilot borehole. The estimated properties are then used as inputs in borehole system design software or manual calculations to determine the size and configuration of the ground heat exchanger (GHE). Even though conducting a TRT has become a standard and a well established practice, the issue of reproducing the TRT results using multiple tests remains largely ignored.

In this paper, we firstly report on the development of a new GSHP test facility and its TRT setup. Secondly, we present an overview of different methods to estimate the undisturbed ground temperature, the ground thermal conductivity and the borehole thermal resistance values from the experimentally obtained TRT data. We then use standard evaluation methods to determine the values of undisturbed ground temperature, ground thermal conductivity and borehole thermal resistance for the borehole field of the GSHP test facility. Comparison of estimated properties for different boreholes of a field provides meaningful insight into the reproducibility issue of TRTs. Next, we investigate the accuracy of the estimated parameters by comparing fluid temperature simulated from these parameters to the experimentally measured fluid temperature. Finally, we use the estimated parameters to simulate the long-term response of the laboratory boreholes. The difference between the long-term responses of different boreholes underlines uncertainties of estimated parameters on the design of a borehole system.

2. TRT SETUP

The Building Services Engineering at Chalmers University of Technology, Sweden has built a new heating, ventilation and air-conditioning laboratory [1]. The new laboratory provides test facilities for experimental studies of various heating, ventilation and air-conditioning systems including BTES and GSHP systems. The new laboratory can be used to test various operation and control strategies for GSHP systems, to develop and validate GSHP system and component models and to conduct TRTs.

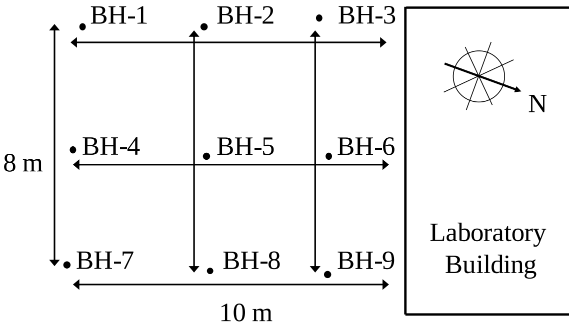

Figure 1: Layout of the laboratory borehole system.

The laboratory's borehole system consists of nine groundwater filled boreholes, each about 80 m deep. The boreholes are drilled in a 3x3 rectangular configuration. The layout of the borehole system is shown in Figure 1. The thermal response setup of the laboratory is shown in Figure 2 and includes a variable capacity electric heater, variable speed circulation pumps and temperature and flow sensors. The circulating fluid temperatures are measured at two instances, firstly when entering or leaving the laboratory building and secondly before and after the heating and cooling source. The flow rate is also measured twice, first using an installed Vortex flow meter and second over the individual borehole valves. The data can be recorded for any interval over 10 seconds.

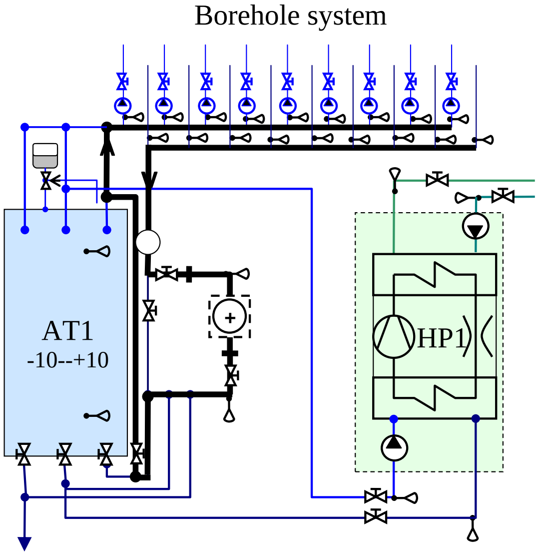

Figure 2: Laboratory's TRT setup.

The laboratory borehole system provides a unique opportunity to study thermal properties including undisturbed ground temperature, ground thermal conductivity and borehole thermal resistance of nine boreholes in close proximity. Such investigations have rarely been conducted on an academic level in controlled laboratory conditions. Issues like repeatability and reproducibility of TRTs can be comprehensively studied using various alternative approaches. The installed electric resistance heater can be used to conduct the thermal response testing in the heat injection mode. It is also possible to conduct TRTs in heat extraction mode using heat pump HP1. Another possibility is to conduct TRTs using fluid at constant input temperature to the boreholes by means of accumulator tank AT1.

3. TEST PROCEDURE

The general procedure of conducting a TRT is to first determine the undisturbed temperature of the ground. Next, a known amount of heat is extracted or injected into the borehole over a certain period of time. It is common to conduct thermal response tests in heat injection mode as it is easier to minimize the influence of external factors affecting the measurements in heat injection mode [2]. Electric resistance heaters are commonly used to inject heat into the ground by heating the circulating fluid. However, a heat pump can also be used to inject or to extract heat from the borehole. The heated fluid is circulated through the borehole for a minimum of 50 hours. The response of the ground is calculated by measuring the inlet and outlet fluid temperatures as a function of time. The readings are generally taken at regular intervals of 1-10 minutes. Other measurements include flow rate of the fluid, power input and the ambient temperature. The measurements are then analyzed using a mathematical heat transfer model to evaluate ground thermal conductivity and borehole thermal resistance.

The following procedure was carried out for the TRTs of laboratory boreholes:

- The flow and the power input were set. The chosen power input of around 55 W/m matched the expected peak loads on the boreholes. The flow from the variable circulation pumps ensured turbulent regime in the ground loop.
- The fluid was circulated through the undisturbed borehole for a minimum of 30 minutes. The inlet and outlet fluid temperatures were recorded at intervals of 10 seconds. The circulation time varied between 30 to 75 minutes for different boreholes.
- The heater was switched on. The power input was monitored and kept steady.
- The inlet fluid, the outlet fluid and the ambient temperatures were recorded together with the flow and power input for time intervals between 3-5 minutes.
- The tests were conducted for a minimum of 48 hours.
- The undisturbed ground temperature, the ground thermal conductivity and the borehole thermal resistance were estimated from the measured data using methods discussed in the next section.

4. TRT EVALUATION METHODS

Various methods can be used to estimate ground thermal conductivity and borehole thermal resistance values from the TRT data. Most of these methods also require the undisturbed ground temperature value as an input. In this section, we discuss how these properties are determined for laboratory boreholes. In addition, we also provide an overview of other available methods to estimate these properties.

The undisturbed ground temperature can be determined using various approaches. One way to estimate the undisturbed ground temperature is by inserting a temperature sensor into an undisturbed borehole. Temperature measurements taken at several points along the borehole can then be used to determine an average undisturbed ground temperature. Another approach to determine the undisturbed ground temperature is to monitor the start-up exit fluid temperature from the U-tube. If the fluid is kept long enough in the U-tube it tends to reach equilibrium with the surrounding ground. The temperature profile of the fluid in equilibrium with the surrounding ground can then be used to estimate the undisturbed ground temperature. In Sweden, the undisturbed ground temperature is usually determined by circulating the fluid through the undisturbed borehole for about

20-30 minutes. The inlet and outlet fluid temperatures are recorded at short time intervals. The recorded temperature profile of 20-30 minutes can then be used to calculate the undisturbed ground temperature. The undisturbed ground temperatures of nine laboratory boreholes have also been determined using this approach.

The ground thermal conductivity and the borehole thermal resistance can be evaluated using direct or parameter estimation methods. Shonder and Beck [3] and Austin [4] have developed numerical methods which determine these thermal properties using parameter estimation techniques. The model of Shonder and Beck solve the 1-D radial heat transfer problem using a finite difference approach and uses Gauss minimization technique to calculate parameter values which minimize the sum of squared errors between predicted and measured fluid temperatures. Austin instead uses a two dimensional finite-volume numerical approach to estimate ground and grout thermal conductivities. The numerical modelling of borehole heat transfer allows the use of time varying heat inputs and is useful for tests with significant power fluctuations. Direct methods, on the other hand, can be used to evaluate the TRTs if the input power is fairly constant. In order to use direct evaluation methods, it is recommended that the input power should have a standard deviation of less than ±1.5 % of the mean input power and a maximum variation of less than ±10 % of the mean input power [5]. The line and the cylindrical source solutions [6] are the two most commonly used direct methods to interpret ground thermal properties from the TRT measurements. Carslaw and Jaeger [7] developed the so called 'probe method' to determine the thermal conductivity using a cylindrical source approximation. The probe method calculates the fluid temperature by approximating the value of the *G-factor* in the classical cylindrical source solution. Plotting calculated fluid temperatures against logarithmic time results in a curve with a linear asymptote. Measuring the slope of the linear asymptote and dividing it by the heat injection rate provides an estimate of the ground thermal conductivity. The second direct method, i.e. the line source solution, has undergone quite a few changes since it was first used. However, the approach used by Gehlin [8] has gained most acceptance because of its simpliciy and ease of use. Gehlin uses the following approximation to determine the mean fluid temeprature T_f.

$$T_f = \frac{q}{4\pi \cdot \lambda_g}\left(\ln\left(\frac{4a \cdot \tau}{\gamma \cdot r_b^2}\right)\right) + q \cdot R_b + T_0 \qquad (1)$$

Here, q [W/m] is the heat injection rate, λ_g [W/(m·K)] is the ground thermal conductivity, a [m^2/s] is the ground thermal diffusivity, τ [s] is time, γ is a constant approximately equal to 1.78, r_b [m] is the borehole radius, R_b [(m·K)/W] is the borehole thermal resistance and T_0 [°C] is the undisturbed ground temperature.

Equation 1 is comparable to Equation 2, which is the equation of a straight line with slope k and intercept m.

$$T_f = k \cdot \ln(\tau) + m \qquad (2)$$

The ground thermal conductivity (λ_g) is calculated using the slope (k) of the fluid temperature line when plotted against logarithmic time ln(τ).

$$\lambda_g = \frac{q}{4\pi \cdot k} \qquad (3)$$

The ground thermal conductivities, reported in this paper, have been calculated using the line source approximation of Gehlin. The borehole thermal resistance values have been determined using the method proposed by Beier and Smith [9]. In their method, Beier and Smith extended the line source approximation to also obtain an estimate of overall borehole thermal resistance using Equations 1 and 3. For any time τ_n, the borehole resistance is determined by Equation 4, using the estimated ground thermal conductivity, the slope of the late-time fluid temperature line, the undisturbed ground temperature and the fluid temperature.

$$R_b = \frac{1}{4\pi \cdot \lambda_g}\left[\frac{T_{f,n} - T_0}{k} - \ln\left(\frac{4a \cdot \tau_n}{\gamma \cdot r_b^2}\right)\right] \qquad (4)$$

5. UNDISTURBED GROUND TEMPERATURE

As discussed earlier, the undisturbed ground temperatures of the laboratory boreholes have been determined by circulating the fluid through the undisturbed borehole. As an example, the undisturbed ground temperature measurement of borehole 2 is shown in Figure 3. As seen from this figure, the circulating fluid temperature tends to stabilize after around 30 minutes of circulation. The stabilized fluid temperature provides a good approximation of the undisturbed ground temperature. One of the potential problems with this approach is that for long circulation times the undisturbed ground temperature measurements get affected by the heat gains from the circulation pump. However, in case of the laboratory boreholes, the use of highly efficient custom made circulation pumps for borehole applications avoided this problem.

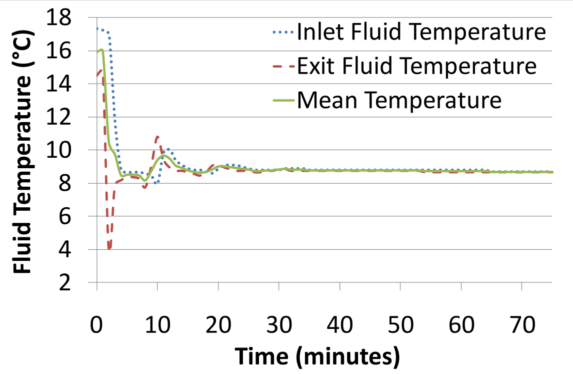

Figure 3: Undisturbed ground temperature for borehole 2.

Table I: Undisturbed ground temperature of laboratory boreholes.

Borehole	Undisturbed Ground Temperature (°C)
BH1	9.1
BH2	8.7
BH3	8.9
BH4	8.5
BH5	8.4
BH6	8.2
BH7	8.2
BH8	8.3
BH9	9.2

Ideally, the undisturbed ground temperature measurements for all nine boreholes should have been similar. But these measurements vary between 8.1 to 9.2 °C. Table I summarizes the undisturbed ground temperature measurements for all the laboratory boreholes. The reason behind different values of undisturbed ground temperature becomes clear when these values are studied together with the corresponding ambient temperatures. The top of the ground layer, surrounding the borehole, is slightly influenced by the ambient temperature changes. Moreover, with the water table for the laboratory borehole system at almost the ground level, the changes in the ambient temperature also affect the top of the water-filled boreholes. The effects of the variations in the ambient temperature, when measuring undisturbed ground temperature, become obvious when the measured values of undisturbed ground temperatures are plotted together with the ambient temperatures in Figure 4. This figure indicates that the undisturbed ground temperature, measured using the fluid circulation approach, has a strong ambient coupling, at least for the laboratory borehole field of rather short boreholes.

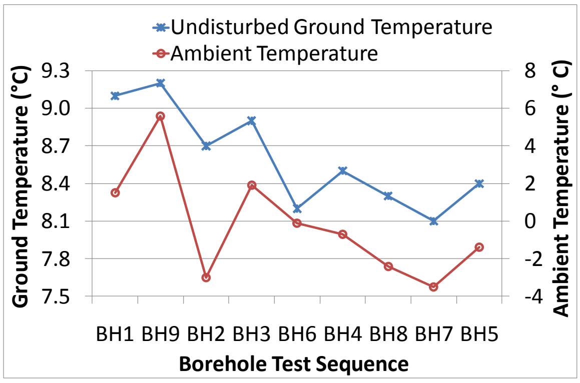

Figure 4: Ambient coupling of the measured undisturbed ground temperatures.

6. GROUND THERMAL CONDUCTIVITY AND BOREHOLE THERMAL RESISTANCE

In order to determine the ground thermal conductivity and the borehole thermal resistance, TRTs were conducted on nine boreholes over a period of three months. The duration of most TRTs was between 68 and 98 hours but tests as short as 48 hours and as long as 267 hours were also conducted. As an illustration, the mean fluid temperature, power input and the ambient temperature measured for the TRT of borehole 3 are shown in Figure 5.

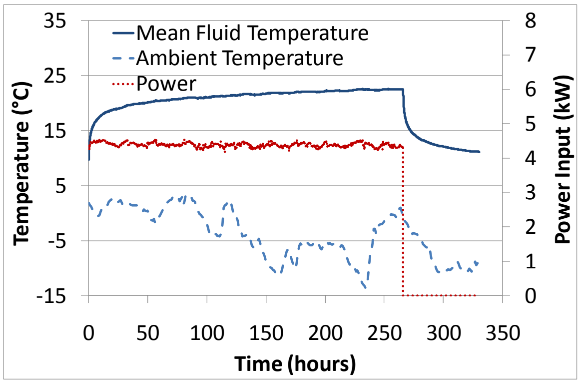

Figure 5: Fluid and ambient temperatures and power input for TRT of borehole 3.

When using the line source approximation, it is common practice to disregard data for times smaller than 10-20 hours. This is because the accuracy of Equation 1 to approximate the fluid temperatures increases with time. The estimated fluid temperatures are sufficiently accurate for times larger than 20 r_b^2/a [8]. For the laboratory borehole system this time translates to around 12.5 hours. Hence, the data of the first 15 hours was disregarded when evaluating TRTs. This is shown in Figure 6, using the example of borehole 3. The figure shows the measured mean fluid temperatures of borehole 3 plotted against the logarithmic time. The data of the first 15 hours is ignored and the trend of late-time (i.e. 15 hours onwards) mean fluid temperature is shown as a dotted line. The slope of this trend line is used as an input to Equation 3 to determine the ground thermal conductivity value. The borehole thermal resistance is calculated from Equation 4. As seen from Equation 4, the estimated value of borehole thermal resistance is linearly related to $(T_{f,n} - T_0)$. The borehole thermal resistance values reported in this paper have been calculated using $T_{f,n}=T_{f,1hr}$. The temperature $T_{f,1hr}$ is the temperature at hour 1, extrapolated from the late-time mean fluid temperature trend. Its numerical value is equal to the intercept value of the trend line shown in Figure 6.

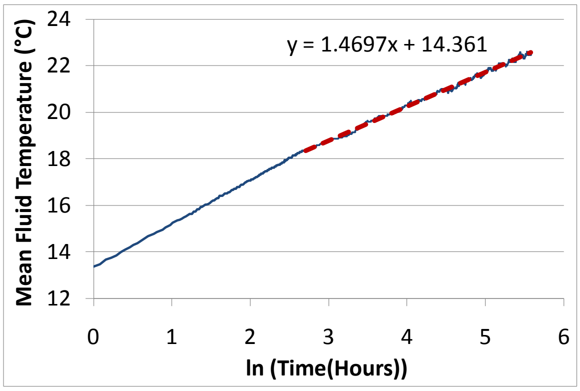

Figure 6: Mean fluid temperature and its late-time trend for borehole 3.

The results of ground thermal conductivity and borehole thermal resistance estimations are summarized in Table II. The ground thermal conductivity estimations for the nine boreholes vary between the extreme values of 2.81 and 3.2 W/(m·K), whereas the estimated values of borehole thermal resistance vary between the extreme values of 0.044 and 0.068 (m·K)/W.

Table II: Ground thermal conductivity and borehole thermal resistance estimations for laboratory boreholes.

No.	Duration (Hours)	λ_s (W/(m·K))	R_b ((m·K)/W)
BH1	75	2.88	0.044
BH2	54	3.06	0.057
BH3	267	3.04	0.063
BH4	48	2.81	0.045
BH5	68	2.98	0.062
BH6	91	2.89	0.065
BH7	48	3.19	0.068
BH8	69	3.20	0.065
BH9	98	3.12	0.053

7. DISCUSSION OF RESULTS

The estimations of ground thermal conductivity and borehole thermal resistance values have noticeable variations. The ground thermal conductivity estimations have a mean value of 3.01 W/(m·K) and the estimated values for all nine boreholes lie within ±7 % of the mean value. On the other hand, the estimated borehole thermal resistance values exhibit larger variations. The borehole thermal resistance values of nine laboratory boreholes lie in a rather wide range of 0.056 ± 0.012 (m·K)/W. As the ground thermal conductivity, the borehole thermal resistance and the undisturbed ground temperature estimations all exhibit considerable variations for the nine laboratory boreholes, the temperatures predicted using these parameters must be checked for their conformance with experimentally measured temperatures. Moreover, the effects of variations in the estimated parameters on the design of a borehole system should also be investigated. In this paper, due to lack of space, we will only look at the effects of the variations in estimated parameters on the design of a single borehole system.

To check the adequacy of the estimated parameters to accurately predict the fluid temperature, the values of undisturbed ground temperature, ground thermal conductivity and borehole thermal resistance are used as inputs in Equation 1 to simulate the mean fluid temperature. Figure 7 presents a comparison of simulated and experimentally measured temperatures for borehole 3. As seen, the fluid temperatures for this borehole are accurately simulated using the estimated parameters. Similar results were also observed for the other eight boreholes.

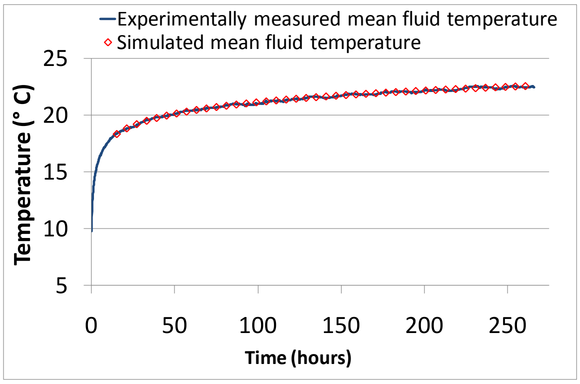

Figure 7: Measured and simulated mean fluid temperatures for borehole 3.

To study the effects of variations in the estimated parameters on the design of a single borehole system, the long-term fluid temperatures of individual boreholes are simulated using the estimated parameters of nine laboratory boreholes. The deterioration of fluid temperatures over time is used as a measure to study the effects of variations in the estimated parameters on the borehole system design. Figure 8 shows the fluid temperatures for nine laboratory boreholes simulated using the line source method. The fluid temperatures are simulated for 25 years of operation using a constant heat flux of 50 W/m. As seen from the figure, the fluid temperatures predicted for nine boreholes have modest variations. The largest variation is between boreholes 6 and 8. Both these boreholes have similar values of borehole thermal resistance but the estimated ground thermal conductivity values vary slightly. The difference in the ground thermal conductivity estimations results in mean fluid temperatures of boreholes 6 and 8 varying by around 0.5 and 2 °C respectively after 1 and 25 years of their operation. Uncertainties like these can typically be countered by adding a few extra meters to the estimated borehole length.

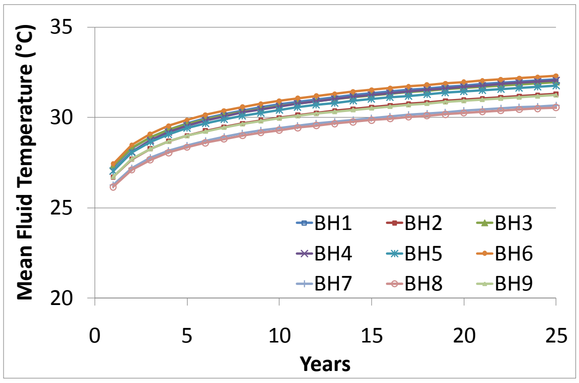

Figure 8: Long-term response of nine laboratory boreholes.

8. CONCLUSIONS

This paper presented the results of TRTs of the borehole field of a new GSHP test facility. An overview of different methods to determine ground thermal conductivity, borehole thermal resistance and undisturbed ground temperature values was also presented. These properties were then calculated for nine laboratory boreholes using the most common evaluation methods. The estimated properties for the nine boreholes showed moderate variations yet the effects of these variations on the design of a single borehole system were found to be rather insignificant.

REFERENCES

[1]Javed, S & Fahlén, P. 2010. Development and planned operation of a ground source heat pump test facility. Newsletter IEA heat pump centre. Vol 28. No 1/2010. pp. 32-35.

[2]Sanner, B, Mands, E, Sauer, M, & Grundmann, E. 2007. Technology, development status, and routine application of thermal response test. Proceedings of European Geothermal Congress. 30th May – 1st June, Germany.

[3]Shonder, J & Beck, J. 1999. Determining effective soil formation properties from field data using a parameter estimations technique. ASHRAE Transactions. Vol 105 (1). pp. 458–466.

[4]Austin, W. 1998. Development of an in-situ system for measuring ground thermal properties. M.Sc. Thesis. Oklahoma State University. USA.

[5]ASHRAE. 2007. Handbook of HVAC Applications. ASHRAE. Atlanta.

[6]Ingersoll, L, Zobel, O & Ingersoll, A. 1954. Heat conduction with engineering, geological and other applications. McGraw-Hill. New York.

[7]Carslaw, H & Jaeger, J. 1959. Conduction of heat in solids. Oxford University Press. Oxford.

[8]Gehlin, S. 2002. Thermal response test - Method development and evaluation. PhD Thesis. Luleå University of Technology. Sweden.

[9]Beier, R & Smith, M. 2002. Borehole thermal resistance from line-source model of in-situ tests. ASHRAE Transactions.Vol 108(2). pp. 212-219.