The effects of test temperature and duration on the results of constant temperature thermal response test

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Abstract

Constant heat flux method is commonly used for Thermal Response Tests (TRT) to predict the thermal properties of a borehole heat exchanger (BHE). An alternative method for TRT is based on constant temperature. Although the cost of this method is relatively higher than that of constant heat flux method, it provides better accuracy and shorter test duration besides well matching with the test standards of heat pumps. The aim of this study is to investigate the effects of test temperature and duration on the long-term predictions based on constant temperature TRT. By using different test durations and fluid temperatures, thermal properties of ground are calculated based on TRT data. Long-term heat transfer rates per unit length of a BHE (unit HTR) are predicted by using the calculated properties of ground. The relative differences between the predictions are compared with each other to examine the dependencies of the predicted unit HTR values on test temperature and duration. The results can be used to determine the suitable and practical duration and fluid temperatures for the applications of constant temperature TRT.

Keywords: Ground source heat pumps; constant temperature thermal response test

1. Introduction

Ground source heat pump (GSHP) system is one of the best sustainable and efficient system for heating and cooling of buildings. Since ground temperature is higher/lower in comparison with that of air for

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winter/summer time, energy efficiency ratio (or coefficient of performance) of a GSHP is always greater than that of air source heat pumps. Borehole heat exchangers (BHE) are commonly used to exchange heat between heat pump and ground. Most of the heat energy (75-80%) transferred from (to) a building goes to (comes from) ground. For this reason, determination of ground properties and prediction of long term performance of BHE are very important not to have capacity problems in the following years after the installation.

To get information about thermal characteristics of BHE and its surrounding ground, Thermal Response Tests (TRT) are widely used around the world. In a TRT process, a certain constant heat flux is injected to ground for a certain period of time. By using a mathematical model for thermal response of BHE, effective thermal conductivity and diffusivity of ground can be obtained. Then these values are used to calculate long term performance predictions of BHE in planning and application stages of GSHP systems.

TRT is first theoretically proposed by Mogensen [1]. He indicated that thermal resistance between fluid and borehole wall can be determined by using heat pump data itself. The first constant heat flux TRT test has been done by himself in 1984 [2]. After Mogensen, Göran Hellström has built a non-mobile test system to determine ground thermal conductivity and borehole thermal resistance [3]. The first mobile test vehicle has been built by Eklöf and Gehlin during their Master's Theses [4]. Then Gehlin [5] improved the constant heat flux TRT method further and done different tests in different boreholes.

Constant heat flux TRT has some problems caused by voltage fluctuations of grid, consuming considerable amount of electrical energy and as well as time to get the results.

In operation of a GSHP, circulation pump of ground side is activated when the compressor is operated and it pumps hot fluid (in cooling mode) or cold fluid (in heating mode) to the borehole. Change in building's heat load causes a change in also heat load of BHE.

During the design process of a GSHP system, the required borehole length is calculated by considering heat load of building, heating/cooling periods, seasonal COP values of heat pump and thermal properties of BHE. The worst possible scenario always prevents any capacity failure. In worst case, circulation pump continuously operates to circulate fluid through BHE. In case of the worst possible scenario, nearly constant fluid temperature condition arises for a long time.

Furthermore, constant temperature conditions are used for brine and load sides during the test of a heat pump according to European standards (EN14511-2) [6]. These values are brine return temperature from the ground and outlet temperature of fluid for load side. During the heat pump test, these temperatures are kept constant then performance rate of heat pumps is determined for different working conditions. Similar to heat pump test, TRT can also be done under constant temperature condition instead of constant heat flux. Indeed, constant temperature TRT has been applied by Wang et.al [7]. They used a cylindrical constant temperature source, modified the Eskilson's [8] derivation for constant temperature and developed a method to obtain thermal conductivity of ground. They mentioned that constant temperature TRT has some important advantages like better accuracy, shorter time to achieve steady state regime and wider range for testing temperature etc.

The acquired data of a constant temperature TRT can be used in analytical or numerical model to make long term performance prediction of a borehole, which is one of the most important criteria in GSHP system design. In this study, an analytical model used in our previous study is improved and then the dependencies of predictions for thermal conductivity and long term (2400 h) unit HTR values on test temperature (2-50^{o} C) and duration (24h-236h) are investigated and practical fluid temperature as well as test duration for constant temperature TRT are proposed.

2. Constant temperature TRT model

During the process of TRT, constant temperature fluid is pumped to a BHE and the difference between inlet and outlet fluid temperatures and volumetric flow rate are measured. Outlet temperature depends on flow rate, inlet temperature, undisturbed ground temperature and thermal properties of ground. After a short time from the beginning of test period, temperature difference becomes more stable and the mean fluid temperature approaches to a constant value during the rest of test period. By considering the constant temperature cylindrical boundary condition, temperature distribution around a borehole can analytically be found.

Although a real BHE consists of PE pipes (U-tubes) and grout, it can be approximated by a simple empty borehole having an equivalent radius and constant wall temperature to get analytical results. Lamarche has showed that equivalent radius approximation gives better results when the borehole is solved as a cylindrical source [9]. Hence, if we assume one equivalent pipe instead of inlet and outlet pipes, the problem becomes easier to solve. The temperature of equivalent pipe is then the mean temperature of fluid. Therefore the problem is reduced to solve the temperature distribution of ground around a borehole with an equivalent radius in terms of time and radial distance.

Equivalent radius can be calculated from the multipole method proposed by Bennet [10]. Lamarche showed that multipole method is the best method in comparison with the others [9]. To calculate the equivalent radius, the following dimensionless parameters are defined by Lamarche;

$$\tilde{r}_{bp} = \frac{r_b}{r_{p,o}}, \quad \tilde{r}_{bc} = \frac{r_b}{x_c}, \quad \tilde{r}_{pc} = \frac{r_{p,o}}{2x_c} \tag{1}$$

By considering the pipe resistance, borehole resistance is given by:

$$R_b = \frac{1}{4\pi k_{gt}}\left[\ln\left(\frac{\tilde{r}_{bp}\,\tilde{r}_{bc}^{\,1+4\sigma}}{2(\tilde{r}_{bc}^4-1)^{\sigma}}\right) - \frac{\tilde{r}_{pc}^2(1-(4\sigma/(\tilde{r}_{bc}^4-1)))^2}{1+\tilde{r}_{pc}^2(1+(16\sigma/(\tilde{r}_{bc}^2-1/\tilde{r}_{bc}^2)^2))}\right] + \frac{1}{2}R_p \tag{2}$$

where $\sigma = \left(\frac{k_{gt}-k_{gr}}{k_{gt}+k_{gr}}\right)$, $R_p = \frac{\boldsymbol{ln}\left(r_{p,o}/r_{p,i}\right)}{2\pi k_p} + \frac{1}{2\pi r_{p,i}h}$ while k_{gt} and k_{gr} are grout and ground thermal conductivities respectively, h is convection coefficient of fluid. In most of the cases, convective resistance is negligible in comparison with the resistance of polyethylene pipe. Conductivity of grout can be known from the laboratory test by the method described in ASTM D5334 [11]. Equivalent radius can then be found from the following equation:

$$r_{eq} = r_b e^{-2\pi k_{gt} R_b} \tag{3}$$

It should be noted that equations for equivalent radius include also thermal conductivity of ground. Therefore an iterative approach has to be used to find ground thermal conductivity and equivalent radius. First an estimated initial conductivity value of ground is used to find an equivalent radius, then constant temperature model is used to predict thermal conductivity of ground by best fitting the experimental heat rate data to the model with the equivalent radius. This process is repeated iteratively until the thermal conductivity value k_{gr} used for r_{eq} becomes equal to the predicted value of k_{gr} by the model.

The mean fluid temperature is $\bar{T} = (T_{in} + T_{out})/2$. Unit heat transfer rate $\dot{q}'$ (unit HTR) can experimentally be determined by

$$\dot{q}'_{\boldsymbol{exp}} = \dot{m}c_p\left(T_{in} - T_{out}\right) / H \tag{4}$$

where $\dot{m}$ is mass flow rate, c_p is specific heat capacity of water at constant pressure and T_{in} is inlet temperature to borehole and T_{out} is outlet temperature from the borehole. By considering the ground as homogeneous and isotropic medium, angular dependencies of temperature can be ignored. Similarly vertical change of temperature can also be neglected since inlet and outlet temperature are so close to each other. Therefore temperature distribution around a borehole can be calculated by the following 1D heat conduction equation in cylindrical coordinates,

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{5}$$

where α is thermal diffusivity defined by $\alpha = k / \rho c_p$, k and ρ are thermal conductivity and mass density of ground respectively. Boundary and initial conditions of the problem are:

$$T\left(r_{eq},\ t\right) = \overline{T}\ ; \qquad T(r\ ,0\,) = T_\infty \qquad T(\infty,\ t) = T_\infty \tag{6}$$

Eq. (5) is simplified by using the following dimensionless quantities:

$$\theta = \frac{T - \overline{T}}{T_\infty - \overline{T}}\ ;\ \ \tilde{r} = \frac{r}{r_{eq}}\ ;\ \ \tilde{t} = \frac{\alpha t}{{r_b}^2} \tag{7}$$

Thus Eq.(5) can be rewritten as

$$\frac{\partial^2 \theta}{\partial \tilde{r}^2} + \frac{1}{\tilde{r}}\frac{\partial \theta}{\partial \tilde{r}} = \frac{\partial \theta}{\partial \tilde{t}} \tag{8}$$

Dimensionless boundary and initial conditions become as follows:

$$\theta(1,\tilde{t}\,) = 0\ ; \qquad \theta(\tilde{r},0) = 1\ ; \qquad \theta(\infty,\tilde{t}\,) = 1 \tag{9}$$

Solution of Eq. (8) under the conditions given by Eq.(9) can be found in literature [12, 13] as follows:

$$\theta(\tilde{r},\tilde{t}\,) = \int_{\beta=0}^{\infty} \frac{\beta e^{-\beta^2\tilde{t}}\left[\mathrm{J}_0(\beta\tilde{r})\mathrm{Y}_0(\beta) - \mathrm{Y}_0(\beta\tilde{r})\mathrm{J}_0(\beta)\right]}{{\mathrm{J}_0}^2(\beta) + {\mathrm{Y}_0}^2(\beta)} d\beta . \int_{r'=1}^{\infty} r'\left[\mathrm{J}_0(\beta r')\mathrm{Y}_0(\beta) - \mathrm{Y}_0(\beta r')\mathrm{J}_0(\beta)\right] dr' \tag{10}$$

The integral over r' in Eq. (10) is analytically solved here and Eq.(10) becomes the following simple form:

$$\theta(\tilde{r},\tilde{t}\,) = \frac{-2}{\pi}\int_{\beta=0}^{\infty} \frac{e^{-\beta^2\tilde{t}}\left[\mathrm{J}_0(\beta\tilde{r})\mathrm{Y}_0(\beta) - \mathrm{Y}_0(\beta\tilde{r})\mathrm{J}_0(\beta)\right]}{\beta\left({\mathrm{J}_0}^2(\beta) + {\mathrm{Y}_0}^2(\beta)\right)} d\beta \tag{11}$$

This expression gives dimensionless temperature distribution around a borehole in terms of dimensionless time and radial coordinate. By using Eq.(11) and equivalent radius, dimensionless unit HTR value can be calculated as

$$\tilde{\dot{q}}'(\tilde{t}) = \frac{\dot{q}'(t)}{2\pi k_{gr}\left(\bar{T} - T_\infty\right)} = \frac{d\theta}{d\tilde{r}}\bigg|_{\tilde{r}=1} = \frac{2}{\pi}\int_{\beta=0}^{\infty} \frac{e^{-\beta^2 \tilde{t}}\left[\mathrm{J}_1(\beta)\mathrm{Y}_0(\beta) - \mathrm{Y}_1(\beta)\mathrm{J}_0(\beta)\right]}{\mathrm{J}_0{}^2(\beta) + \mathrm{Y}_0{}^2(\beta)} d\beta \qquad (12)$$

For a given value of time $\tilde{t}$, $\tilde{\dot{q}}'(\tilde{t})$ can be calculated by numerical integration of Eq.(12) in Mathematica environment [14]. The calculated data is fitted to experimental data by the following equation:

$$\tilde{\dot{q}}'\left(\frac{t\,k_{gr}}{r_{eq}{}^2 \rho c_p}\right) = \frac{\dot{q}'_{exp}(t)}{2\pi k_{gr}\left(\bar{T} - T_\infty\right)} \qquad (13)$$

Since the quantities r_{eq} , $\bar{T}$, T_∞ and experimentally measured unit HTR values $\dot{q}'_{exp}(t)$ are known for a given time *t*, k_{gr} can numerically be determined by an iterative way. Least square method is used during the iterative solution of k_{gr} by Eq.(13). Although the value of volumetric heat capacity ρc_p of ground changes in between 1.8-3.0 MJ/m^{3}K, the predicted value of k_{gr} weakly depends on the change in value of ρc_p . Indeed, 62% change in ρc_p causes only 8% change in k_{gr} [15]. Therefore, the value of volumetric heat capacity ρc_p is usually estimated after the observations during the drilling process [16]. Consequently, k_{gr} is iteratively calculated as explained in detail at Section 2. The effects of test temperature and test duration on the predictions of k_{gr} are investigated in the following sections.

3. Experimental study

Constant temperature TRT system, in Istanbul Technical University Energy Institute, mainly consists of a water tank with electrical heater and chiller, circulating pump, PID control unit and data logger, (Fig. 1 and Fig. 2). By using this system, more than one borehole can simultaneously be tested as well as each U-tube can be tested separately.

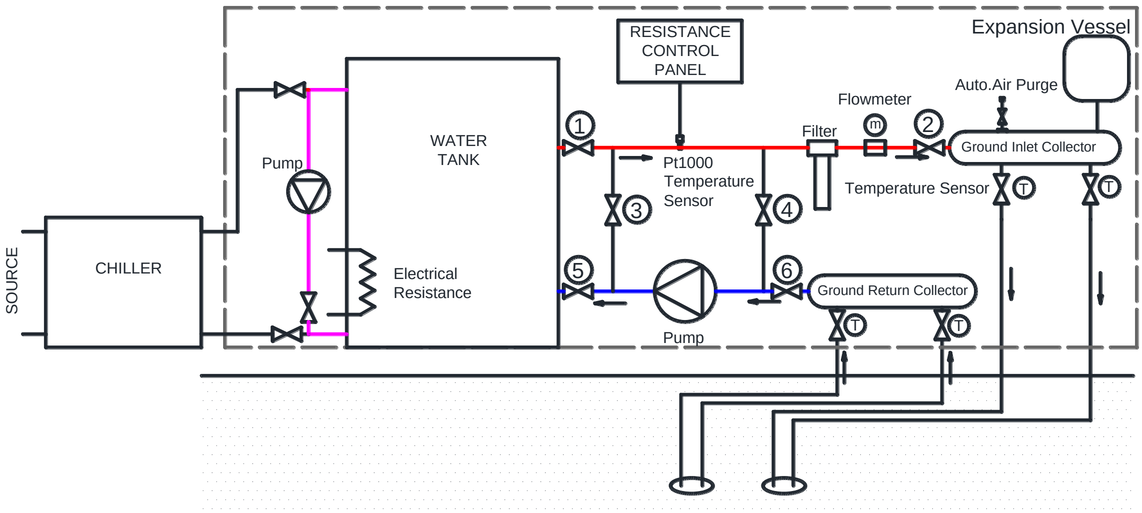

Fig. 1. Thermal Response Test system.

Fig. 2. Snapshots from TRT vehicle and testing process.

During a sample test of 40 ^{o}C, time variations of inlet, outlet and mean temperatures of a borehole are given in Fig.3. Inlet temperature is always kept constant during the test and variations of mean temperature decrease in time and it converges a constant value. Undisturbed ground temperature is measured according to ASHRAE method, [17]. It is simply based on measurement of outlet temperature of fluid from a borehole which rest for a long time. In other words, temperature of water, which exits the borehole immediately after the circulating pump is operated, gives the undisturbed ground temperature. Time interval between successive TRT experiments is at least 20 days. Before each TRT experiment, undisturbed ground temperature is measured to check whether the initial value is recovered. Measurements show that the difference between undisturbed ground temperature of each TRT and that of the first TRT is less than 0.2 ^{o}C.

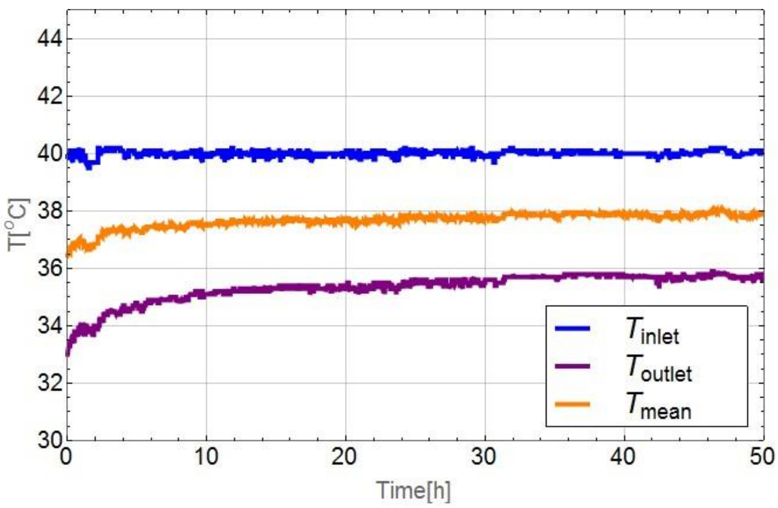

Fig. 3. Inlet, outlet and mean temperature variations during the test for 40 °C inlet temperature.

4. Effect of test temperature

Table 1 shows test conditions and the predicted thermal conductivities based on Eq.(13) of a 50m borehole for different inlet temperatures. Both experimentally measured and the calculated unit HTR values after thermal conductivity predictions are shown in Fig.4 for different inlet test temperatures. For the water temperatures below the undisturbed ground temperature, unit HTR values become negative as expected. To show all HTR values on positive axes, absolute unit HTR values are used. Fig. 5 shows the predicted conductivity values versus inlet temperature. It is seen that the predicted thermal conductivities are the same between 5-40 °C while it is slightly different for 1.9 °C and 50 °C inlet temperatures. The mean value and standard deviation of thermal conductivity are 2.27 W/m °C and 0.07 (3%). To obtain fluid temperatures lower than undisturbed ground temperature, it is necessary to use relatively expensive chillers. Instead, it is better to choose warmer test temperatures, which can be obtained by using a simple heater, to minimize the investment costs. In order to minimize also the operational costs, much higher test temperatures than the undisturbed ground temperature should be avoided as long as accuracy of temperature sensors is high enough. Therefore, it seems that fluid temperatures which are around 15 °C higher than the undisturbed ground temperature are sufficient if the accuracies of sensors for inlet and outlet temperatures are good enough. In the case here, 30 °C seems suitable test temperature. On the other hand, in case of less accuracy or high uncertainty of sensors, it is necessary to increase the difference between inlet and outlet temperatures to decrease the relative error. Then, the higher test temperatures become necessary.

Table 1. Different temperature test conditions and the predicted thermal conductivities.

		Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Inlet temperature	°C	**1.9**	**5.0**	**30.0**	**40.0**	**50.0**
Volumetric flow-rate	lt/min	16.0	16.0	16.0	16.0	16.0
Avg. outlet temperature	°C	4.6	7.0	27.3	35.4	43.2
Mean temperature	°C	3.3	6.0	28.7	37.7	46.6
Predicted Thermal Conductivity	W/mK	**2.38**	**2.27**	**2.27**	**2.27**	**2.18**

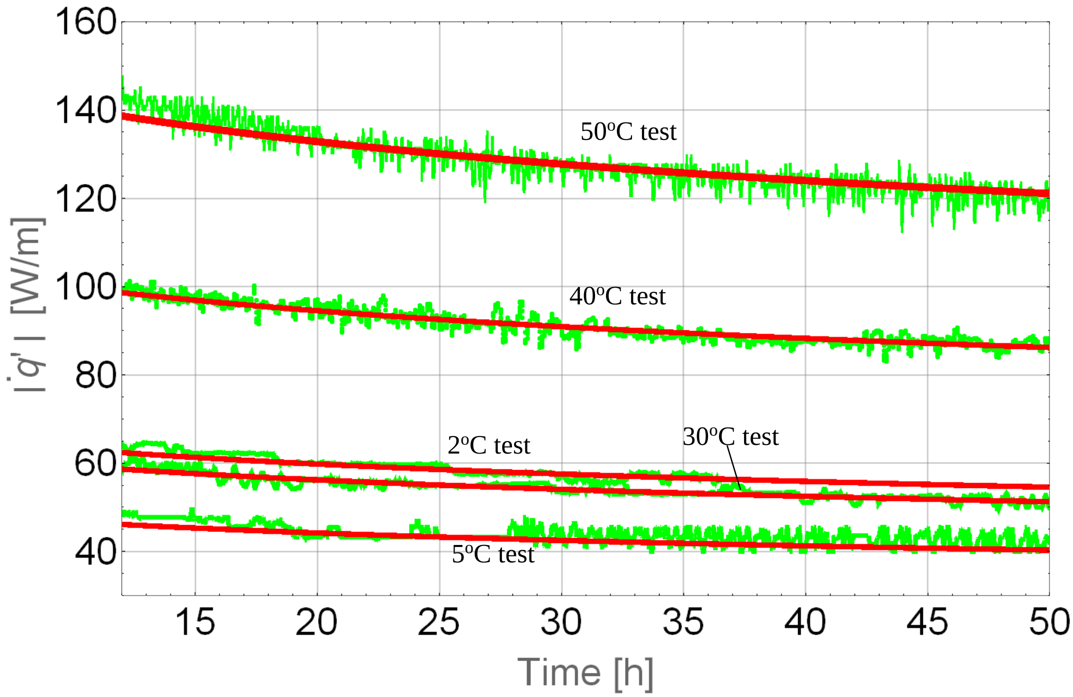

Fig.4. Experimental data (fluctuating curves) and fitted (solid) curves by using Eq.(13) for different test temperatures.

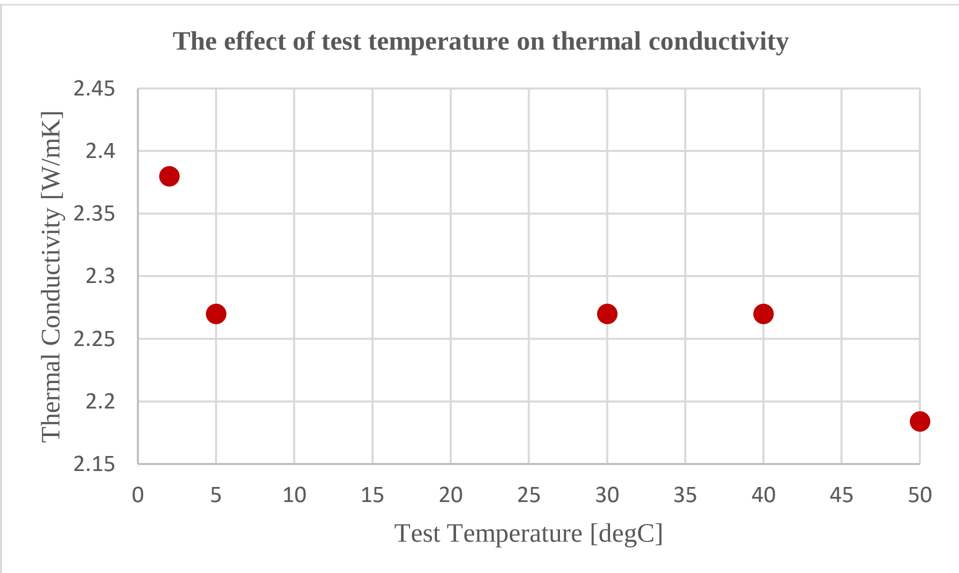

Fig. 5. Predicted thermal conductivities for different test temperatures.

5. Effect of test duration

To find suitable test duration, thermal response test is applied only for 236 hours. Then, thermal conductivity of a borehole is repetitively predicted by considering Eq.(13) and different duration of the same data. The relative differences between the predicted thermal conductivities based on 24h, 48h, 72h, 96h and 120h data and the reference prediction based on 236h data are given in Table 2. Furthermore predictions for unit HTR value at the end of 2400h operation are made by using different durations of data and their values are given in the same Table.

Table 2. The predicted thermal conductivity results and their relative differences for different test durations.

Test Duration (h)	Thermal conductivity W/m	Relative Difference (%)	Unit HTR prediction at the end of 2400 h
24	2.23	1.8	58.6
36	2.20	0.5	58.0
48	2.19	-	58.0
72	2.19	-	58.0
236	2.19	-	58.0

Steady-state condition inside the borehole is reached after about 9-12h from the beginning of the test. Therefore the first 12h data are omitted due to the assumption used in analytical model. Using the rest part of 24 h test data, thermal conductivity is predicted as 2.23 W/mK. On the other hand, the same value of 2.19 W/mK is predicted by 48h and longer data. There is only about 2% difference between the results of 24h and 236h. Therefore it can be said that 24-36 h test duration is quite enough to obtain reliable results with minimal operational cost.

6. Conclusion

In this study, a model is briefly introduced based on constant temperature and equivalent radius approximation. Then the effects of test temperature and duration on the results are investigated. It is seen that there is no significant differences between the predicted thermal conductivities based on different test temperatures and durations. Therefore, 24-36 h test duration and around 15 ºC warmer test temperature than the undisturbed ground temperature can be used to get reliable results and minimize both investment and operational costs as long as accuracies of sensors are high enough. The results can be helpful to optimize thermal response test (TRT) conditions before the engineering design stages of GSHP systems.

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Nomenclature	
T	Temperature (°C)
$\overline{T}$	Mean temperature (°C)
$\dot{q}$	Heat transfer rate (W)
$\dot{q}'$	Unit heat transfer rate (W/m)
$\tilde{\dot{q}}'$	Dimensionless heat transfer rate
$\dot{m}$	Mass flow rate (kg/sec)
C_p	Heat Capacity (J/(kg K))
r	Radius (m)
$\tilde{r}$	Dimensionless radius
t	Time (sec)
$\tilde{t}$	Dimensionless time
x_c	Shank spacing (m)
k	Thermal Conductivity (W/(mK))
H	Borehole length (m)

Greek Letters	
ρ	Density (kg/m^3)
α	Thermal Diffusivity (m^2/s)
β	Integration constant
Subscript	
in	inlet
out	outlet
∞	Undisturbed, far field
gr	ground
gt	grout
b	borehole wall
p	Pipe
eq	Equivalent
p,o	Pipe outer
p,i	Pipe inner