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Effect of test parameters on the recovery of underground after a Thermal Response Test and optimum waiting time between tests

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ABSTRACT

Thermal Response Test (TRT) is an important method to determine the thermal properties of underground. These tests can be interrupted by unexpected reasons and a new test must be started in the same borehole, or the test must be repeated because of various reasons. In this paper, optimum waiting duration for a second test after a completed TRT is investigated through analyzing thermal behavior of a borehole during and after the test. A computational model is built, and it is verified with an experimental test. After the verification, the numerical model is used further parametric investigations. Different cases are considered and the results are discussed. The effect of thermal conductivity and test duration on the minimum waiting times are also investigated. It is shown that optimum waiting duration depends highly on the test conditions, however it varies between 10 and 23 days.

1. Introduction

Ground source heat pumps (GSHPs) use underground as a heat source to provide thermal energy for heating or a heat sink to remove the heat for cooling. In recent years GSHP systems are getting more popular due to their advantages like being local energy resource and environmentally friendly, having low emissions, comparatively high performance and their low operating costs [1,2]. Generally, in a GSHP system, thermal energy of underground is transferred to the buildings by circulation of fluid in the pipes that are installed in the ground. The performance of a GSHP is highly dependent on the working parameters of ground heat exchangers (GHE) that can built vertically or horizontally [3]. Underground is an unknown environment and some tests and studies must be carried out before an application. Especially thermal properties of underground are important parameters which can affect performance of the heat pump system [4–7]. By knowing the thermal properties of underground, one can predict the future thermal performance of GHE and the heat pump system. Under sizing of boreholes in design stage may lead poor thermal performance in the future usage of the system and oversizing can increase the initial price and become the system as unfeasible to invest [8,9]. For these reasons, correct design of a system is crucially important. In order to design a system correctly, accurate measurement of ground properties is also quite important. Thermal response test (TRT) can provide the thermal properties of underground [10,11]. In this test, temperatures of fluid in the inlet and outlet of the heat exchangers are measured, and the thermal properties of the underground is determined using the line source model or the cylindrical source model [12]. TRTs are often performed on one or a few borehole/s of a large BHE field [13].

The idea of TRT was firstly proposed by Mogensen [14] and the first experimental devices were developed simultaneously at the Lund University and Oklahoma State University in the concept of constant heat flux injection for determination of thermal conductivity of borehole [15,16]. Until today, many studies were conducted on TRT, and a comprehensive review about recent studies on the TRT for GSHP can be found in the review of Zhang et al. [17]. Generally, TRTs are classified as constant heat flux [18] or constant temperature tests [19] in aspect of the method of giving heat energy to the borehole. The initial one, i.e. the conventional TRT which is based on the constant heat-flux method has been using widely. However, the constant temperature method is relatively new and it has some advantages and can provide more sensitive results [20]. Choi et al. [21] numerically investigated these two methods and compared them in terms of heat transfer process.

Generally, performing a conventional TRT in a borehole lasts approximately two days [22], and an amount of heat energy is injected continuously into the BHE during this time. This supplied heat energy is usually generated from an electrical source. In some cases, more than one test is required for a borehole and sometimes the test must be

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Fig. 1. Snapshots from TRT vehicle during a testing process.

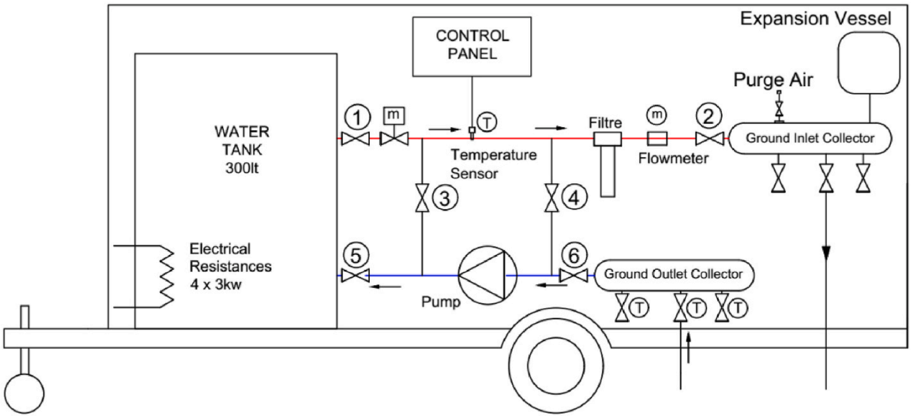

Fig. 2. Thermal Response Test system.

repeated due to problems during the test or poor quality of the results or in some cases, a new test is required after a completed TRT to verify the results. Especially in boreholes for research purposes, many tests are required for different aims. Furthermore, an ongoing test may be interrupted due to problems such as electric cut-off or failure in data acquisition etc. In fact, continuing the test after an interrupted test may provide similar results [23,24]. However, the test should be continued immediately after the interruption or a period of time has to be waited for recovering of the ground temperature.

After a heat-injected-TRT or shortly after a drilling process, vertical temperature distribution of the borehole largely varies than its initial profile. The thermally affected spatial volume around the borehole depends on the test duration and the amount of the given heat energy to the borehole, i.e. more heat energy induces more thermally effected area. After a heat injection process, the recovery of the ground temperature starts immediately, and it takes normally very long time. In the literature, there is limited information about the required waiting time to recover for a thermally effected borehole. The recovery period of a borehole after a TRT was investigated by Raymond et al. [25]. They also used temperature evaluations on the recovery period to find the thermal properties of a borehole. In this period, a significant amount of recovery takes place at the first hours. Then, the rate of decline in temperature decreases and it takes a very long time to completely return to the initial temperature. In fact, the temperature profile does not return to its initial condition in practical time durations, however, it approaches to the initial condition. Between the initial and the final temperature an approach value can be used. If the difference between the final and the initial temperature is lower than the approach value it can be said the recovery is completed. Raymond et al. [25] used two different approach values as 0.5 °C and 0.1 °C to calculate the required time for the temperature to become uniform in the borehole. The ASHRAE advises to wait at least 14 days for a new test after a completed test [22]. Javed et al. [26] also experimentally investigated the recovery times after TRT on BHEs. Their results indicate that the recovery of the ground temperature to the initial conditions can take longer than existing recommendations. The results also show that the required recovery period is strongly related to the duration of the TRT and the heat injection rate.

In this study, optimum waiting time between two tests is examined by analyzing the thermal behavior of a borehole during and after a completed test. A computational model was built and validated with the experimental data. After the validation, the numerical method is used for further parametric investigations. Various cases are considered and the results are discussed in the following sections and minimum waiting times for different tests were also calculated.

2. Experimental setup

In order to test our borehole a special TRT device that is shown in Fig. 1 was used. The working scheme of the TRT device is given in Fig. 2. This device can perform constant temperature TRT as well as conventional TRT with constant heat flux. The TRT system measures inlet/outlet fluid temperatures, air temperature and flowrate of circulating fluid. Mainly the TRT device consists of water tank with electrical resistances, a circulation pump, temperature sensors, a flowmeter, a data logger and other fitting and control equipment. Before the tests, turbine type flowmeter and Pt1000 temperature sensors were connected to the laboratory devices in Heat Pumps Test and Research Laboratory of Istanbul Technical University Energy Institute. The laboratory is equipped with a number of A type Pt1000 temperature sensors and flowmeters, which have already undergone calibration. At the calibration flexible inlet and outlet pipes of TRT device were connected to the laboratory test system (the details can be found in Refs. [27,28]. Since the temperatures on both sides show the same values, this was considered adequate for the calibration. The specifications of the measuring

Table 1

Specifications of the flowmeter and the temperature sensors.

Flow meter		
Nominal Diameter	15	mm
Repeatability	±0.2	%
Accuracy – Standard	±1	%
Temperature Sensor		
Type	Pt1000	
Precision	±0.15	K

Fig. 3. Temperature sensor that located on pipe.

devices are given in Table 1. The water tank given in Fig. 2 provides stability of constant temperature of the water and prevents fluctuations in the inlet fluid temperature. As can be seen from Fig. 2, in the TRT device two by-pass lines have been added intentionally, one is before the pump, the other is after the pump. With the help of these by-pass lines various tests can be realized.

In order to measure the undisturbed ground temperature by using the water circulation method [29], valves numbered as 1, 4 and 5 are closed and the pump is started, the edge of the pipes in the borehole are connected to the test system, the air is purged from the system and the circulating water in the pipes gives the undisturbed temperature of the ground after a while. It also can be measured by recording the return fluid temperature with short time intervals immediately after the pump is started, as recommended by ASHRAE [22]. After measuring the undisturbed ground temperature, test can be started, to perform a test, valves 3 and 4 are closed and the others are opened. For constant temperature test case, at first, the fluid in the water tank has to be heated up to the desired test temperature. By closing the valve 2, 3 and 6 and starting the pump the fluid can be heated up. The test parameters can be entered from the control page of device, also it can be controlled remotely on internet by using any mobile device. After reaching the test temperature in the water tank, the test can be started by opening the valves from collectors and 1, 2, 5 and 6. Valve 3 is kept closed during the test, however, the previous tests showed that opening of 10–15 % of valve 4 provides mixing of the return and the inlet fluids and thus more stable temperature can be provided.

Picture of the temperature sensor that measures the ground temperature is given in Fig. 3.

3. Modeling and validation

A sketch view and cross-sectional view of the borehole is given in Fig. 4. In the numerical model, properties of ground and grout are assumed as isotropic and homogeneous. In the model, undisturbed ground temperature is applied as far-field boundary condition for the ground domain. Domain size of the ground is chosen big enough to ensure that temperature changes nearby BHE are not affected by the boundaries of the ground domain. In the real borehole that was used in the experiment, a groundwater flow was not detected and it is also neglected in the model. Therefore, only conductive heat transfer is considered in the numerical analysis. The numerical solutions are obtained in OpenGeoSys (OGS) [30]. OpenGeoSys (OGS) is a scientific open-source project for the development of numerical methods for the simulation of thermo-hydro-mechanical-chemical (THMC) processes in porous and fractured media. Specifications of the borehole and material parameters of the domains used in the numerical model are given in Table 2. The geometrical parameters are the design and measured values recorded during the construction of the borehole, only ground domain is the domain radius applied in the modeling. Thermal properties of the PE pipe and grout were taken directly from the manufacturers. Ground properties were derived from the Thermal Response Test conducted on the borehole [19]. Ground temperatures were measured in different

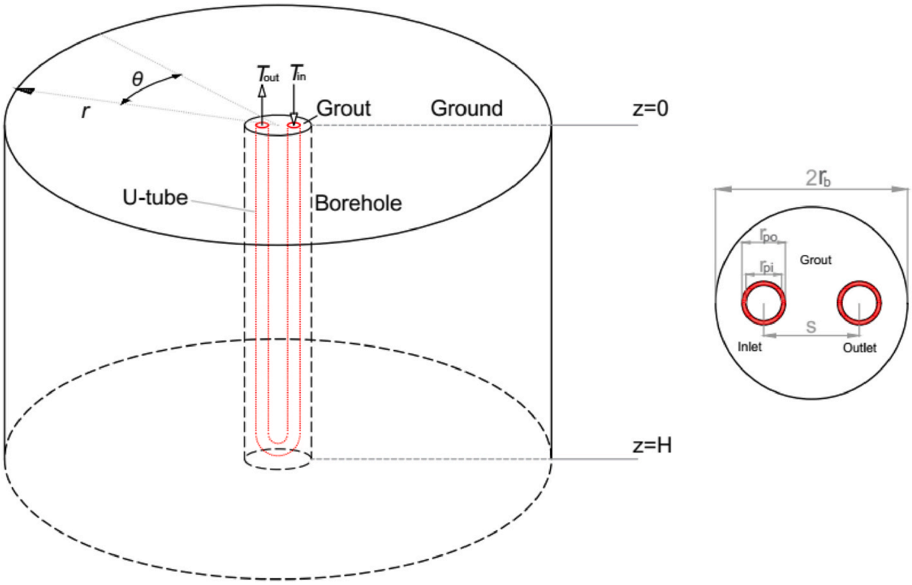

Fig. 4. Drawings of the borehole.

Table 2
Geometrical parameters, material properties and initial conditions.

SYMBOL	VALUE	QUANTITY
Geometrical properties		
r_d	10	Radius of the ground domain [m]
r_b	0.088	Radius of the borehole [m]
r_{pi}	0.0131	Inner radius of the pipe [m]
r_{po}	0.0160	Outer radius of the pipe [m]
S	0.097	Shank space [m]
H	50.0	Borehole depth [m]
Thermal properties of PE pipe		
λ_{pe}	0.38	Thermal conductivity [W $m^{-1}K^{-1}$]
C_{p_pe}	1900	Specific heat capacity [$Jkg^{-1}K^{-1}$]
ρ_{pe}	959	Density [kg m^{-3}]
Thermal properties of grout		
λ_{gt}	1.4	Thermal conductivity [W $m^{-1}K^{-1}$]
C_{p_gt}	900	Specific heat capacity [$Jkg^{-1}K^{-1}$]
ρ_{gt}	1500	Density [kg m^{-3}]
Thermal properties of ground		
$\lambda_{gr.}$	3.1	Thermal conductivity [W $m^{-1}K^{-1}$]
C_{p_gr}	800	Specific heat capacity [$Jkg^{-1}K^{-1}$]
ρ_{gr}	2130	Density [kg m^{-3}]
Initial condition		
T_∞	14	Undisturbed ground temperature [^oC]

times from the temperature sensor integrated in the test system.

Governing equations in the domains:

$$k\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

where k, ρ and c_p are thermal conductivity, mass density and specific heat capacity of the domain respectively.

Boundary conditions are given as, in the periphery of inlet pipe: T_{in} and in the periphery of outlet pipe: T_{out}. Far field temperature in the radial distance where is not affected thermally from the test:

$$\lim_{r\to\infty} T(r,t)=T_\infty \tag{2}$$

and initial condition is also equal to the undisturbed ground temperature:

$$T(r,t=0)=T_\infty \tag{3}$$

and boundary conditions in the recovery process

$$T(r,t_l)=T_l(r) \tag{4}$$

where t_l is start time of the recovery and T_l is the horizontal temperature profile of the borehole immediately after the test. Initial condition of the recovery process is the last radial temperature distribution around the borehole. The temperature distribution is calculated numerically and used as initial condition in the solution of the recovery period. As the effects are negligible, heat transfers through the top and bottom surfaces are disregarded.

Mesh structure is another significant parameter that can affect the results in finite element modeling. The mesh structure that is used in the numerical modeling is given in Fig. 5. To keep the number of total mesh elements at a rational level, an adaptive mesh selection is used, i.e. the regions around the borehole were finely meshed, the far regions from the BHE were coarse meshed. It is seen that the number of 19854 mesh elements is adequate to get sufficiently precise and mesh independent results.

To validate the model, experimentally recorded inlet and outlet temperatures from the BHE were used. Fig. 6 shows variation of temperature results at 15 m depth for experimental and numerical data during the TRT process and the recovery period. The test was completed in the test field of Istanbul Technical University with the TRT device shown in Fig. 1. The temperature sensor that measures the data on the outer side of the PE pipe is at the 15m depth of BHE. Effects of daily air temperature to the ground, pipe and also to the fluid inside the pipe are negligible in the test duration. Furthermore, these changes of air temperature have not considerable effect on the recovery of the ground as

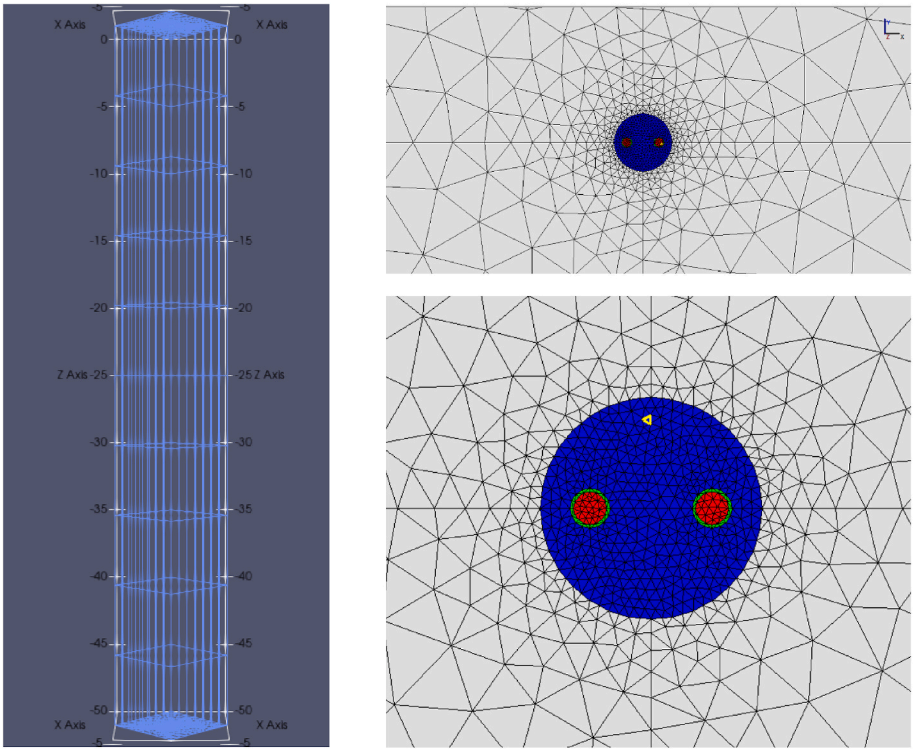

Fig. 5. Mesh structure of the numerical model.

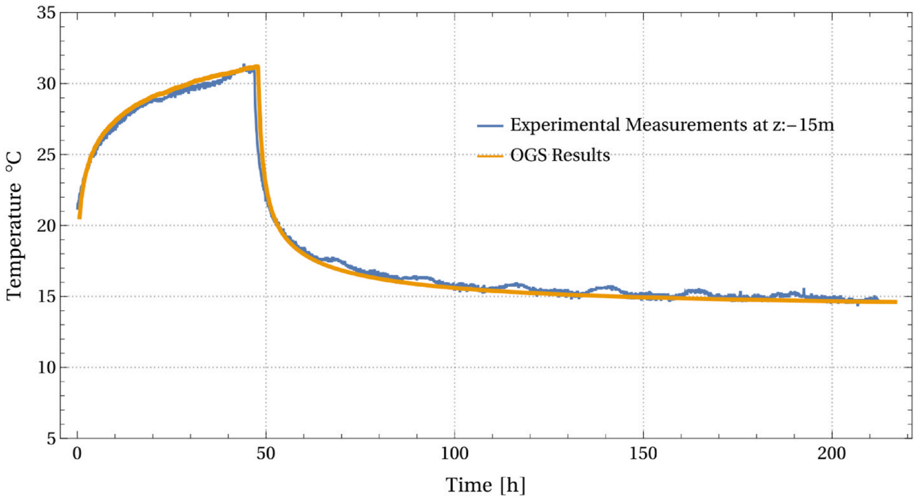

Fig. 6. Comparison between experimental and numerical results at 15 m depth during the TRT process and the recovery period.

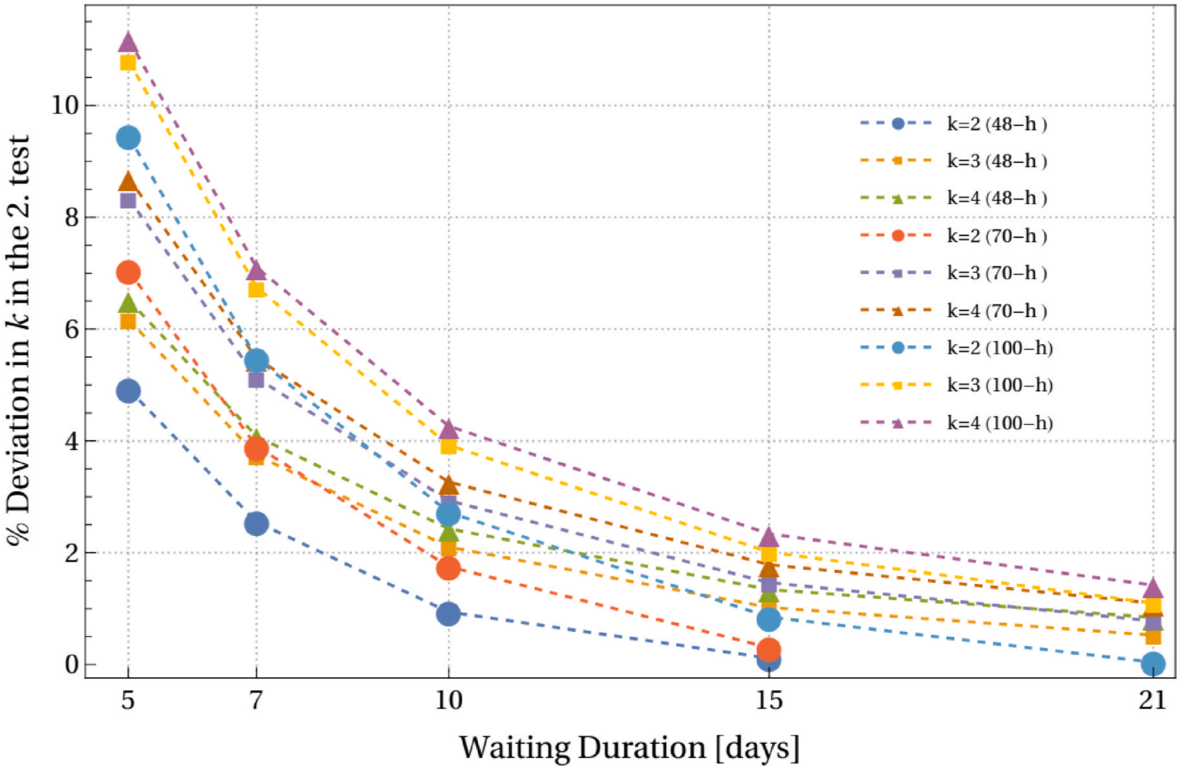

Fig. 7. Difference in the thermal conductivity values in the second TRT for different waiting durations.

can be also in Fig. 6. Moreover, as can be seen from Fig. 6, more than half of the recovery occurs first hours after the termination of heat injection. Further recovery occurs slower than the first phase, as time passes the recovery rate also decreases, even after one week the temperature cannot reach the initial temperature that is measured before the test. The initial temperature was measured as 14 °C and the temperature after one week was measured as 14.8 °C.

As can be seen from Fig. 6, there is a good agreement between the experimental results and the numerical results for both heat injection and the recovery periods. Hence, the same model is validated with the experimental results and it can be used for further analysis as given in the following section.

4. Results

The numerical model is used in parametric investigations of the different thermal properties of the ground. The thermal properties of the ground are entered as input values to the model, then the model was run. In the model, heat is injected into the ground for a certain period of time in the first TRT by applying a unit heat flux to the inner surfaces of both the inlet and outlet pipes. During the subsequent waiting period, no heat flux is applied, instead, the injected heat dissipates from inner pipe surfaces to the surrounding environment. After the following waiting period, the second TRT is started and the same amount of heat injected into the ground again. After getting the data of circulating fluid temperatures, thermal conductivity of the underground is calculated analytically for the both tests.

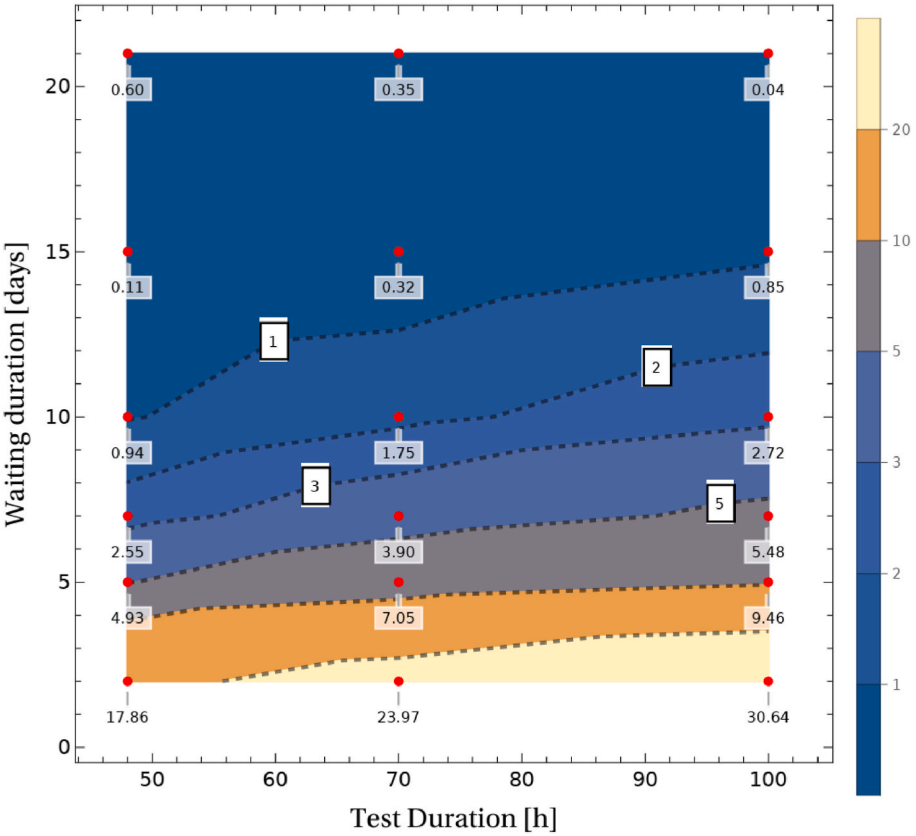

Fig. 8. Test duration –deviation % deviation and waiting duration plots.

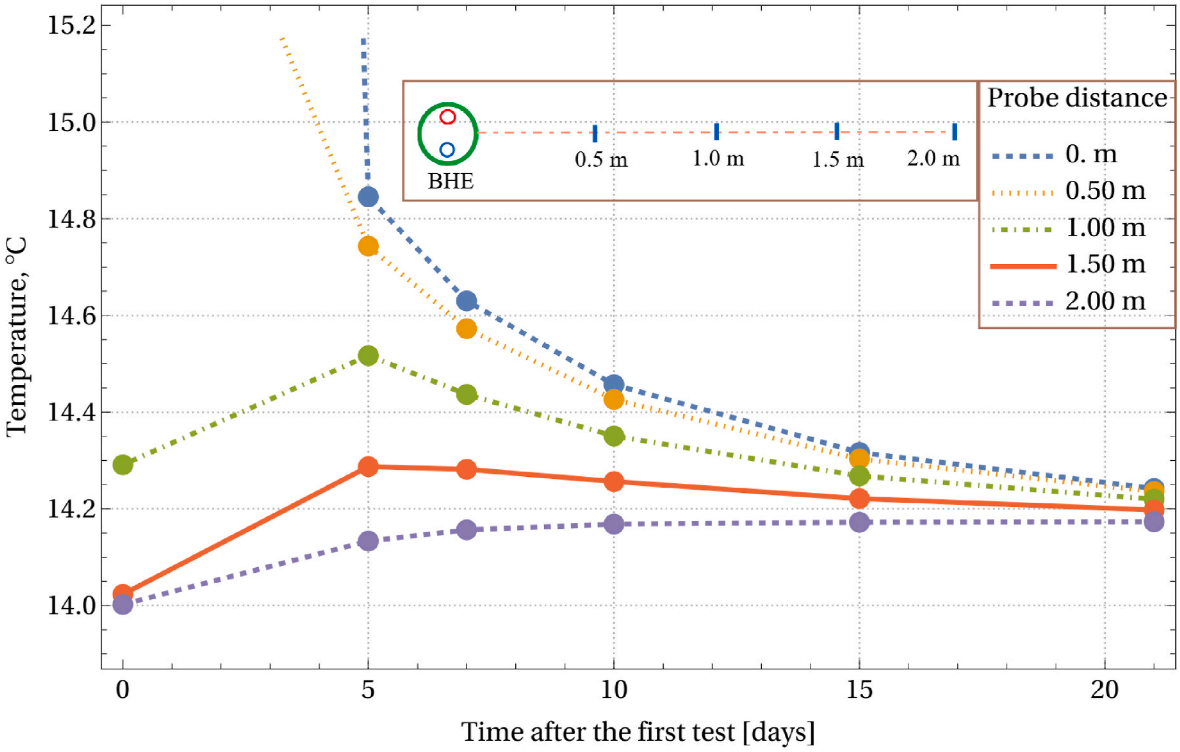

Fig. 9. Variations of temperature with time in different distances.

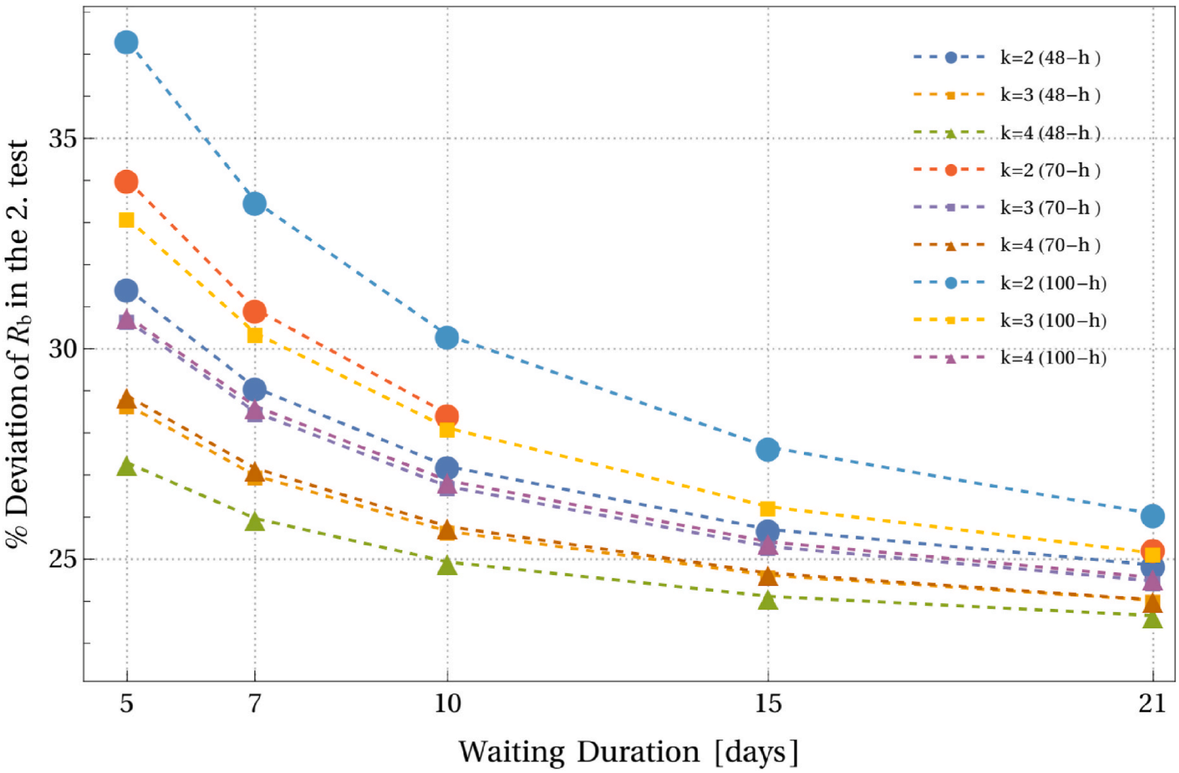

Fig. 10. Difference in the thermal resistance values in the second TRT for different waiting durations.

It is also important to investigate significant parameters that can have a considerable effect on the thermally affected area around the borehole during a TRT. These parameters can be given as test length, waiting duration after the first test, heat rate applied to the borehole and thermal conductivity of the ground. Correspondingly the parametric investigations were performed for different test lengths (48, 70 and 100 h), several waiting durations (2, 5, 7, 10, 15 and 21 days) and different ground thermal conductivity (2, 3 and 4 W/mK) conditions, they are totally 54 different scenarios.

Fig. 7 shows the calculated thermal conductivity deviations in the second test for different waiting durations and different thermal conductivity values in tests that were performed in different test durations. For all cases, the deviations of the thermal conductivity in the second tests were found as lower than 2.5 % with 15 days waiting duration. This derivation values are less than 1 % when thermal conductivity is 2 W/mK. However, with 21 days waiting duration difference between the thermal conductivities are lower than 1.5 % nearly for all cases. In 100-h test, because of highly change of the initial temperature in the first test, more differences were obtained in the second TRT than the others in higher thermal conductivities.

Deviation of the thermal conductivities in the second test can be seen more clearly also in Fig. 8. Where x and y represent the test durations

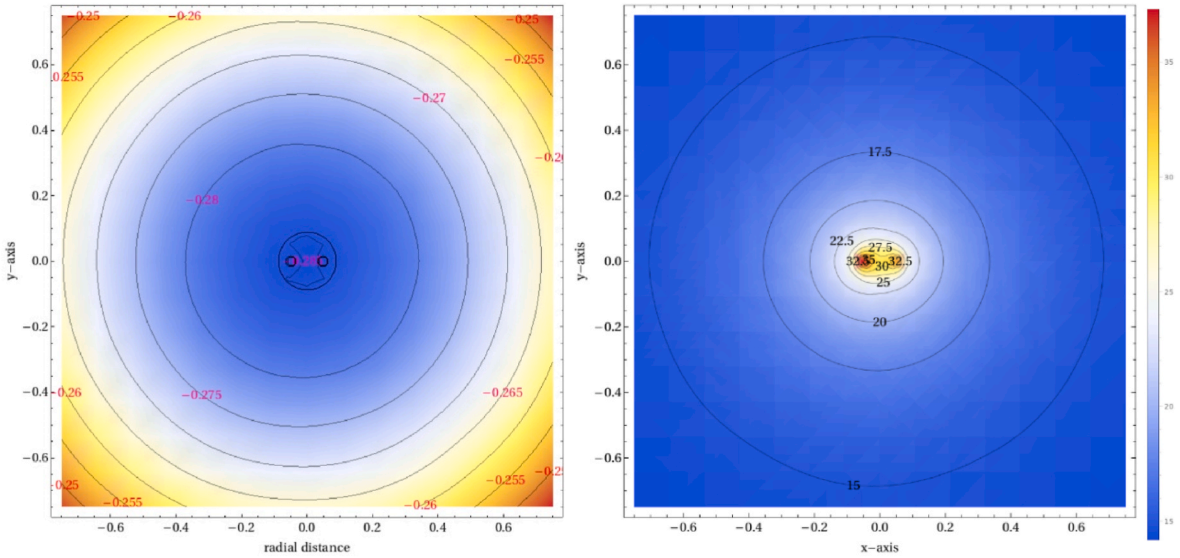

Fig. 11. Temperature differences between end temperatures of first and second TRTs (left) and temperature distribution after the second test (right) for 48-h with 21-day waiting and $k = 2$ W/mK.

Table 3
Thermal conductivities and %deviations for all cases.

Thermal Conductivity Values (W/mK)								
input *k*	Test Length	1. TRT	2.TRT					
			2 days	5 days	7 days	10 days	15 days	21 days
k = 2	48 h	1.98	2.30	2.05	2.01	1.98	1.97	1.96
	70 h	1.99	2.40	2.09	2.04	2.00	1.97	1.96
	100 h	2.00	2.51	2.13	2.06	2.01	1.98	1.97
k = 3	48 h	3.00	3.52	3.15	3.08	3.04	3.01	3.00
	70 h	3.00	3.69	3.20	3.12	3.06	3.02	3.00
	100 h	3.01	3.86	3.27	3.16	3.09	3.04	3.01
k = 4	48 h	4.01	4.73	4.22	4.13	4.07	4.04	4.02
	70 h	4.02	4.95	4.30	4.18	4.10	4.05	4.03
	100 h	4.02	5.19	4.38	4.24	4.14	4.07	4.04

% deviations								
input *k*	Test Length	1. TRT	2.TRT					
			2 days	5 days	7 days	10 days	15 days	21 days
k = 2	48 h	1.20	14.77	2.72	0.61	0.78	1.68	2.09
	70 h	0.52	20.03	4.52	1.75	0.10	1.36	1.89
	100 h	0.14	25.63	6.54	3.07	0.70	0.88	1.63
k = 3	48 h	0.09	17.45	4.95	2.76	1.30	0.36	0.06
	70 h	0.16	22.94	6.82	3.95	2.01	0.74	0.15
	100 h	0.35	28.81	8.93	5.32	2.85	1.20	0.42
k = 4	48 h	0.22	18.15	5.55	3.34	1.87	0.92	0.49
	70 h	0.40	23.71	7.45	4.54	2.58	1.30	0.70
	100 h	0.52	29.65	9.58	5.93	3.44	1.76	0.97

and waiting duration in the second test respectively. Contours in the figure indicate % deviations in the second test.

Temperature changings of underground in the vicinity of the borehole for different distances from the center are given in Fig. 9 for the 70-h TRT and 15-days recovery case. After 20.day temperature profile around the borehole is approached closely to the initial condition. Ground temperature in the further points (2 m, 1.5 m and 1 m) from borehole wall continue to increase even after stop of the test as can be seen from the corresponding curves in the figure. In these points, up to 5 days the temperatures are increased then they start to decrease. However, in the vicinity of the borehole decrease of temperature starts immediately after stop of the test because of these closer regions are quickly affected from the thermal properties of the underground.

Fig. 10 depicts deviations of the thermal resistance values of BHEs in the second TRTs for the different cases. Differently from the thermal conductivities, the thermal resistances are differing largely for the same scenarios of thermal conductivities. For 21-days recovery the deviation is around 25 % that is quite high than the difference of thermal conductivities. The reason can be given as that the initial temperature immediately before start affects highly the thermal resistance results. In the first TRT initial temperature is the undisturbed underground temperature, however in the second test the residual heat deviates the initial temperature than the first test. In the first test R_b is obtained as 0.197 mK/W, in the calculation of the second test when the undisturbed underground temperature that was existed before the all test is used R_b is obtained as 0.245. However, when the average temperature in the region of a virtual cylinder in the center with 7 m radius is used R_b is obtained as 0.243, similarly when the average temperature in a virtual cylinder with 4 m radius is used R_b is obtained as 0.241 mK/W.

Difference between the initial temperatures can be seen better in the left plot in Fig. 11. The figure shows plot of differences end temperature distributions from the two tests that were completed for 48-h with 21-day waiting and $k = 2$ W/mK. Immediately before the start of the second test there is 0.25–0.28 K difference in the initial temperature. The right figure shows normal temperature distribution end of the second test.

Borehole thermal resistance can be also calculated with so-called Multipole method according to the [31]. With this method it is obtained as 0.191 mK/W as it is also almost same with the thermal resistance calculation in the first test.

Table 3 shows all thermal conductivity and Table 4 shows thermal resistance values from the all the considered cases. It can be also seen that thermal conductivity values are always very close to real value when it is calculated by using last periods of the tests. For example, the data after 36 h produce closer results.

4.1. Minimum waiting time

Amount of heat that is injected to the underground affects duration of thermal recovery in the underground. Fig. 12 shows optimum waiting

Table 4
Borehole thermal resistance and %deviations for all cases.

Thermal Resistance Values (m.K/W)								
input *k*	Test Length	1.TRT	2.TRT					
			2 days	5 days	7 days	10 days	15 days	21 days
k = 2	48 h	0.194	0.274	0.255	0.250	0.247	0.245	0.243
	70 h	0.195	0.284	0.261	0.255	0.251	0.247	0.244
	100 h	0.196	0.295	0.268	0.260	0.255	0.250	0.247
k = 3	48 h	0.197	0.266	0.253	0.250	0.248	0.246	0.244
	70 h	0.197	0.274	0.257	0.253	0.250	0.247	0.246
	100 h	0.198	0.282	0.262	0.257	0.253	0.250	0.247
k = 4	48 h	0.198	0.262	0.251	0.249	0.247	0.245	0.244
	70 h	0.198	0.267	0.254	0.251	0.248	0.246	0.245
	100 h	0.198	0.274	0.258	0.254	0.250	0.248	0.246

% deviations								
input *k*	Test Length	1.TRT	2.TRT					
			2 days	5 days	7 days	10 days	15 days	21 days
k = 2	48 h	1.75	40.8	31.3	29.1	27.3	25.8	25.0
	70 h	2.38	45.2	33.5	30.6	28.2	26.2	25.1
	100 h	2.77	50.4	36.5	32.8	29.8	27.3	25.7
k = 3	48 h	3.15	35.2	28.5	26.9	25.6	24.6	24.0
	70 h	3.32	38.7	30.3	28.2	26.5	25.2	24.4
	100 h	3.44	42.6	32.6	30.0	27.8	26.1	25.0
k = 4	48 h	3.44	32.5	27.1	25.8	24.8	24.1	23.6
	70 h	3.52	35.2	28.6	26.9	25.6	24.6	24.0
	100 h	3.58	38.3	30.4	28.3	26.7	25.3	24.5

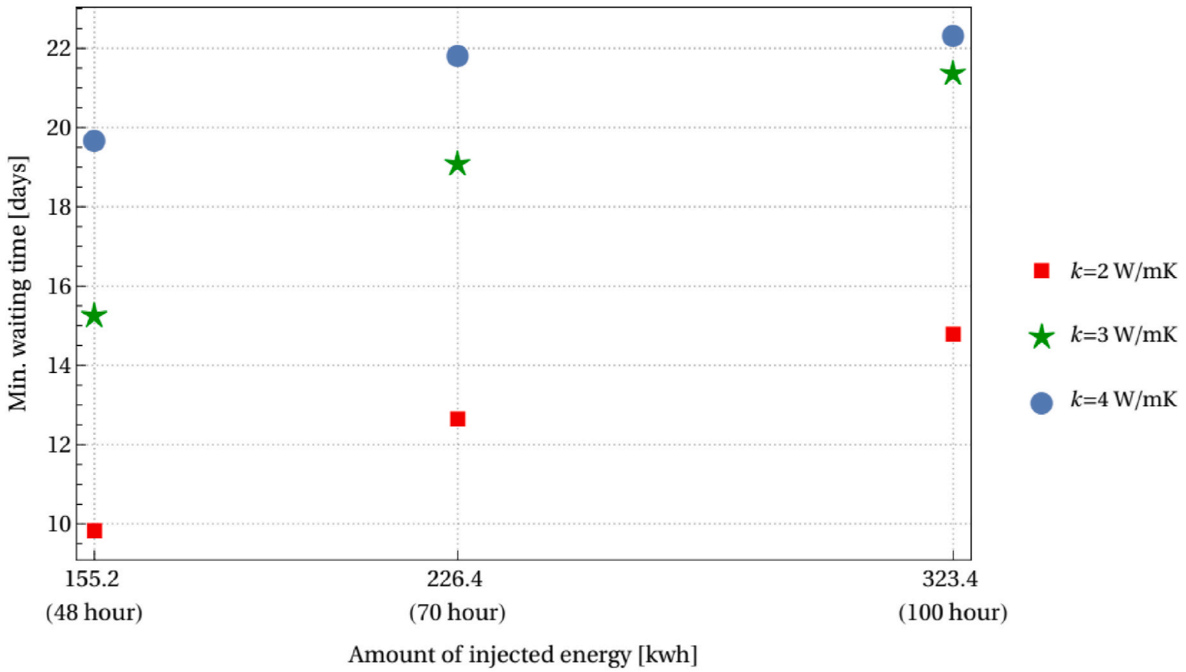

Fig. 12. Optimum waiting durations for different thermal properties of underground considering deviation in the results as 1 %.

duration after the first test to get the same thermal conductivity. Here the approach values are used as 1 %. For a thermal conductivity 2 W/mK and 48-test duration 10-days waiting is enough for starting a new test in the same borehole. However, for higher thermal conductivities like 4 W/mK minimum 20-days waiting must be considered. For the all cases maximum optimum waiting duration is lower than 23-days. When the injected amount of energy is decreased, effect of the thermal conductivity to the minimum waiting duration is also decreased.

5. Conclusion

In this study, optimum waiting duration between two Thermal Response Tests in a borehole is investigated by changing the parameters that can have a considerable effect on the thermally affected area around the borehole during a TRT. These parameters are test length, waiting duration after the first test and thermal conductivity of the ground. Totally 54 different scenarios are considered and parametrically investigated. It is seen that recovery speed of a borehole strongly depends on thermal properties of underground. According to the results, waiting duration is not same for all tests. Recovery time is affected highly from test duration and thermal conductivities of underground. For higher thermal conductivities minimum waiting duration is 20–22 days, however for 2 W/mK and 48-h test optimum waiting duration is 10-days. For 15 days waiting duration, the deviations of thermal conductivity of underground is lesser than 2.5 % for all the investigated cases. When 21 days are waited after the first test, the deviation is lesser than 1.5 %. However, the deviation in the borehole thermal resistance is always found very high in the calculation of second test results because of sensitivity of intercept point. In the calculation of borehole thermal resistance, instead of ILS, the Multipole method can be used.

The results of this study can be instructive for determining optimum waiting duration between two thermal response tests in borehole heat exchangers. Furthermore, they could be useful for academic studies and for end users to achieve results that are more reliable in limited time and the results can be used during the engineering design process of a borehole field to eliminate unnecessary waiting period.

CRediT authorship contribution statement

Murat Aydin: Conceptualization, Funding acquisition, Project administration, Writing – original draft. **Ahmet Gultekin:** Formal analysis, Investigation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest on the manuscript that is titled as *Effect of test parameters on the recovery of underground after a Thermal Response Test and optimum waiting time between tests*.

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Nomenclature

c_p: Specific heat capacity at constant pressure (J/(kg K))
d: Day
h: Hour
$\dot{q}'$: Unit heat transfer rate (W/m)
R: Thermal Resistance (mK/W)
T: Temperature (^{o} C)
t: Time (s or h)
r: Radius
k: Thermal conductivity (W/mK)
ρ: Density (kg/m^3)

Subscripts

b: Borehole
d: Domain
f: Fluid
gr: Ground
gt: Grout
i: internal
in: inlet
out: outlet
pe: Polyethylene
∞: Undisturbed, far field
l: Last data after the test
0: initial

Abbreviations

BHE: Borehole Heat Exchangers
GHE: Ground Heat Exchangers
GSHP: Ground Source Heat Pump
TRT: Thermal Response Test