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Determining Thermal Conductivities of Boreholes by Immersed Probes Using the Constant Temperature Test

Murat Aydin and Rolf Bracke

GZB - International Geothermal Centre, Bochum University of Applied Sciences, 44801 Bochum, Germany

murat.aydin@hs-bochum.de

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ABSTRACT

In designing of Ground Source Heat Pumps (GSHP), Thermal Response Tests (TRT) provide a profound basis for the final implementation. With a TRT, the effective thermal conductivity and thermal resistance of a borehole can be obtained. Until today, several TRT types have been introduced as Constant Heat Flux TRT, Constant temperature TRT, Enhanced GRT and more. In this study, we introduce a new simple thermal conductivity obtaining method that can be used for boreholes. Generally, TRTs are applied with the circulation of water inside pipes or immersing probes in water. In the case of applying water circulation in deep boreholes, different heat flux values will correspond to different layers. Moreover, giving constant heat flux similar to conventional TRT into a water-filled borehole or a water-filled pipes results in convective movements of water and this may disrupt the results. However, using immersed probes as a heat source to keep the temperature constant might prevent water convection cells inside a pipe or borehole. In order to keep the water temperature constant along the borehole, application of different heat fluxes will be required for different layers. These heat flux values mainly depend on the thermal conductivity values of the layers. Therefore, the thermal conductivity of each layer can be approximated by using the heat flux values obtained from the test. This method is investigated in this study and it is shown that thermal conductivities of layers can be obtained by applying a constant temperature test by immersed probes.

1. INTRODUCTION

In the applications of ground source heat pumps, thermal properties of ground are crucial parameters that are used in design processes. Inaccurate measurements of thermal properties can lead a wrong design and the wrong design can waste the all investment. One of the most important parameters of the ground used in design processes is the thermal conductivity. For measuring of thermal conductivities various methods have been introduced until today. Most of the methods are based on being released one of the variables of the heat equation while keeping the others constant. In the heat equation in cylindrical coordinates ($q = k\ \partial T/\partial r$), one of two variables ∂T or q can be released while keeping the others constant during a period of time. During the period of test, thermal conductivity (k) may also vary but this variation strongly depends on the medium in which heat transfer takes place. In the boreholes that used in ground source heat pump systems, ∂T or q can be kept constant and from the trend of change of the released variable, thermal conductivity of the borehole can be found. The most commonly used method is the q-constant test as is used in the conventional Thermal Response Test, in this test an amount of heat is given to the borehole throughout the test, and the thermal conductivity is predicted from the changes of temperature of circulated fluid in the borehole. Furthermore, in T-constant test, the fluid temperature in the borehole is kept constant and different heat fluxes are given during the test time (Aydin et al. 2019). From the trend of heat fluxes, the thermal conductivity of borehole can be predicted similar to the q constant test.

However, in order to give an amount of heat flux to a borehole, circulation of fluid is not compulsory, the required heat flux also can be supplied by cables. Tests with cables in boreholes have been tried in some previous studies (Marquez et al. 2018, Tombe et al., 2018). However, T-constant test with cables has not been tried before. By using heating cables and temperature sensors the fluid temperature can be kept constant and from the change of heat fluxes thermal conductivity can be obtained. Maintaining a constant temperature along water column in the borehole does not allow formation of convective motion cells, which is the one of the major problems of the q-constant tests with cables. The T-constant tests have also some other advantages in comparison with the conventional tests (Wang et al., 2010). Furthermore, validness of constant-temperature-TRT has been shown previously for fluid circulated tests (Aydin et al. 2019).

In this study, feasibility of constant temperature test with cables for boreholes is investigated. The method is described and validated with a numerical model. The developed numerical model is used for further validation in an experimental data that have thermal conductivity profile of a borehole that is already obtained with other methods.

2. METHOD

In the testing process with heating cables, the cables and sensors are lowered inside of fluid filled U-pipe from the both sides. The heating cables provide heat energy for the test and the temperature sensors read the temperatures of different sections along the borehole. The heating cable and temperature sensors are connected to a control system on the surface. The amount of heat flux that is required to provide constant temperature is adjusted by the control system. A schematic view of the test method is given in Figure 1.

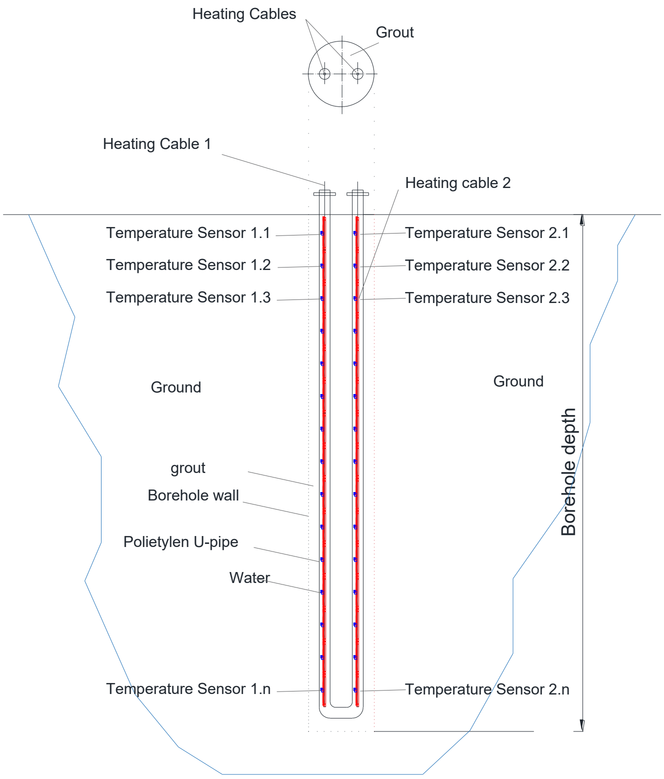

Figure 1: Thermal Response Test with cables.

In order to keep the temperature constant through the borehole there should be a connection system between the temperature sensors and heating cable. In theoretically each point through the borehole may have different thermal conductivities and for each point different heat fluxes correspond. That also indicates that for each corresponding sensor, different heat fluxes need to be given. However, for a practical application, for our current knowledge, this kind of technology is not mature and not available yet in the market. However, with available technologies temperature can be easily measured and the heat energy can be supplied with heating cables. Since we cannot give the corresponding heat fluxes for each point of depth of the borehole, we have to divide the test probe to different sections. Number of the sections can be changed from 1 to *n*. One section means that there is only one heating section and the heat flux that is going to be given to the borehole will be calculated by using the average value of the temperatures of all the sensors on the probe. If there will be two sections, the heat flux of each section will be calculated using the average of the temperature sensors of the corresponding section (Figure 2). If the section number is increased, the sensitivity of the result also will be increased.

Implementation of constant water temperature along the borehole also provides constancy of temperature in the vicinity of the borehole, thus the vertical heat transfer between the layers of ground can be neglected.In fact, as the distance from the borehole is increased, some temperature differences between the layers can be seen. However, vertical temperature differences in these far regions will be less than the difference in the horizontal plane where the heat transfer dominantly takes place.

In Figure 2, a vertical cross-sectional view of a borehole is shown and the borehole is vertically discretized to different layers each horizontal layer has *h* height. Depending on the test system discretization can be decreased until 1 layer as is shown in the same Figure.

The heat equation in the cylindrical coordinates:

$$q'(t) = -2\pi k\left(r\frac{dT}{dr}\right). \quad (1)$$

In the borehole wall i.e. at the left boundary, temperature is equal to the test temperature:

$$T((r = r_e), t) = T_{test}. \quad (2)$$

where r_e is the equivalent radius. The equivalent radius approximation is adopted from the multipole method (Javed and Spitler 2016) that is the best in comparison with others (Lamarche et al., 2010). The equivalent radius is necessary only for numerical validation case however, in the calculation of thermal conductivity (Eq.4), it is not needed.

In the heat flux calculation for the *n*-layer case, different heat fluxes have to be given for each layer (Aydin et al. 2019). Each layer has different initial temperature as $T_{\infty i}$, hence the corresponding heat flux will be equal to:

$$q_i(t) = \frac{4\pi k\left(T_{test} - T_{\infty i}\right)}{\left[\ln(t) + \ln\left(4\alpha / \left(e^{\gamma} r_e^2\right)\right)\right]} \qquad \text{for } i = 1 \ldots \text{n} \qquad (3)$$

hence, thermal conductivity of the layer can be obtained:

$$k_i = \frac{1}{4 m_i \pi \left(T_{test} - T_{\infty i}\right)} \qquad \text{for } i = 1 \ldots \text{n} \qquad (4)$$

For the n/2-layers case, the undisturbed ground temperatures will be different:

$$T_{\infty}{}' = \left(T_{\infty i} + T_{\infty i+1}\right) / 2 \qquad \text{for } i = 1 \ldots \text{n} \qquad (5)$$

and m and k values also will be different. As the layers are decreased, the undisturbed temperature will be average of the temperature of the layers. For 1-layer case, the undisturbed temperature is:

$$T_{\infty}{}^{n} = \sum_{i=1}^{n} \left(T_{\infty i}\right) / n \,. \qquad (6)$$

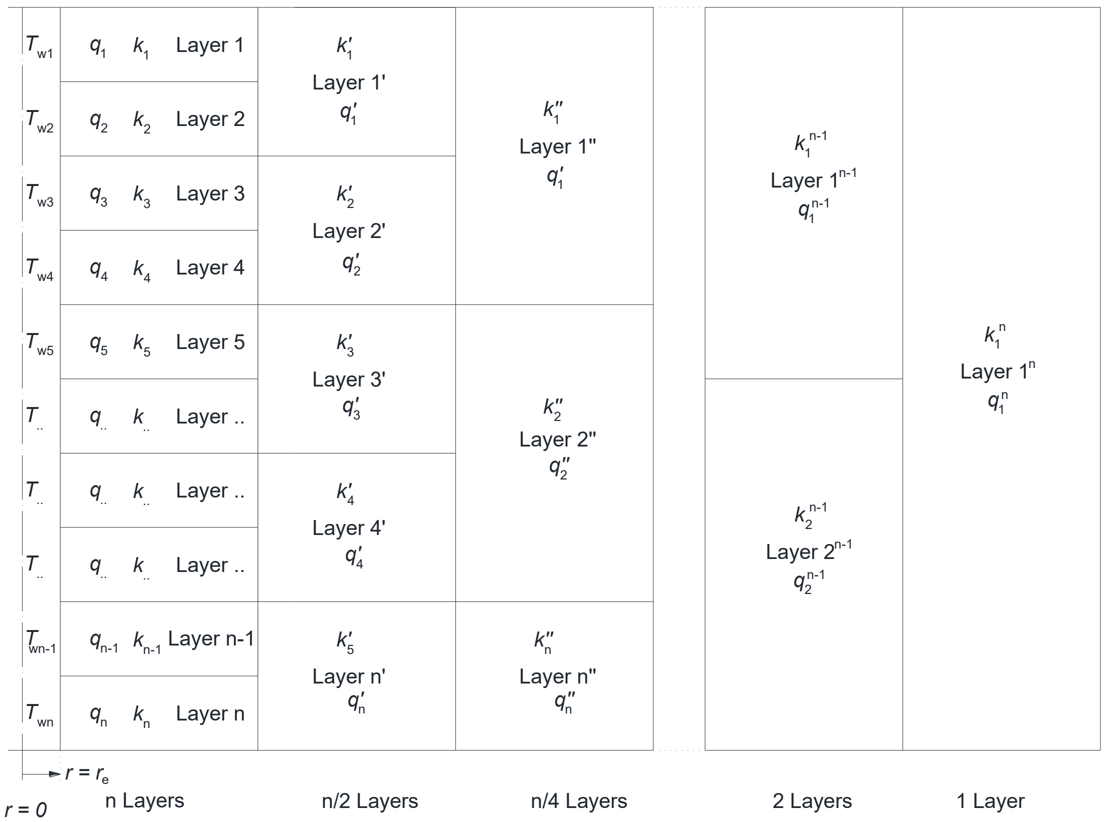

Figure 2: Different discretization in the borehole.

Thermal conductivity value of each layer can be obtained by using Eq.4 for different discretization. Thus with combination of thermal conductivity of values, a thermal conductivity profile of a borehole can be drawn. For n-layers case, the profile will be more detailed, however, for 1-layer case, one agglomerate value will be obtained like in the conventional TRTs. The validation of the method with a numerical model is given in the following section.

3. VALIDATION

For validation of the method, a borehole whose thermal conductivity profile previously is known is used. As is well known, initial some depth of a borehole can be affected from the air temperature changings. Therefore, in this analysis, the first 20 m of the borehole is disregarded and thermal conductivity profile of the borehole between the 20 m and 70 m is used. The real borehole is also equipped with a fiber optic cable that can give temperature data for each 0.5 m. If the discretization is implemented for h=0.5 m, for 50 m length of the borehole, we will have 100 layers. It can be called as n-layers (n=100) case. For the n/2 layers case 50 layers each has 1 m height are obtained, and for the n/4 case 25 layers each has 2 m height are obtained and so on. Here, only n (100 layers), n/2 (50 layers), n/4 (25 layers), n/10 (10 layers) and n/20 (5 layers) cases are investigated.

As is given in Figure 2, 50 m part of the borehole is discretized for different n cases. In the first case(*n*-case) for every 0.5 m of the borehole, there is a corresponding heating section and it makes total 100 sections. For the n/20 case, there are 5 sections each has 10 m length. Thermal conductivity of layers was obtained for each layer and for each case and then different thermal conductivity profiles are obtained for different cases. Comparison of the obtained thermal conductivity profiles of different cases is given in Figure 3. In the Figure, previously known thermal conductivity profile of borehole section is also given. For the cases in which the height of section larger than 1 m thermal conductivity measurement is assumed to be taken from the middle of the section. As is seen from the Figure 3 for 0.5 m, 1 m and 2 m-section cases are very close the fiber-optic results. However, for 5m-section and 10 m-section coarser profile are obtained than 0.5 m case. However total deviation from the first case is approximately 6% for 5m and 10 m-sections.

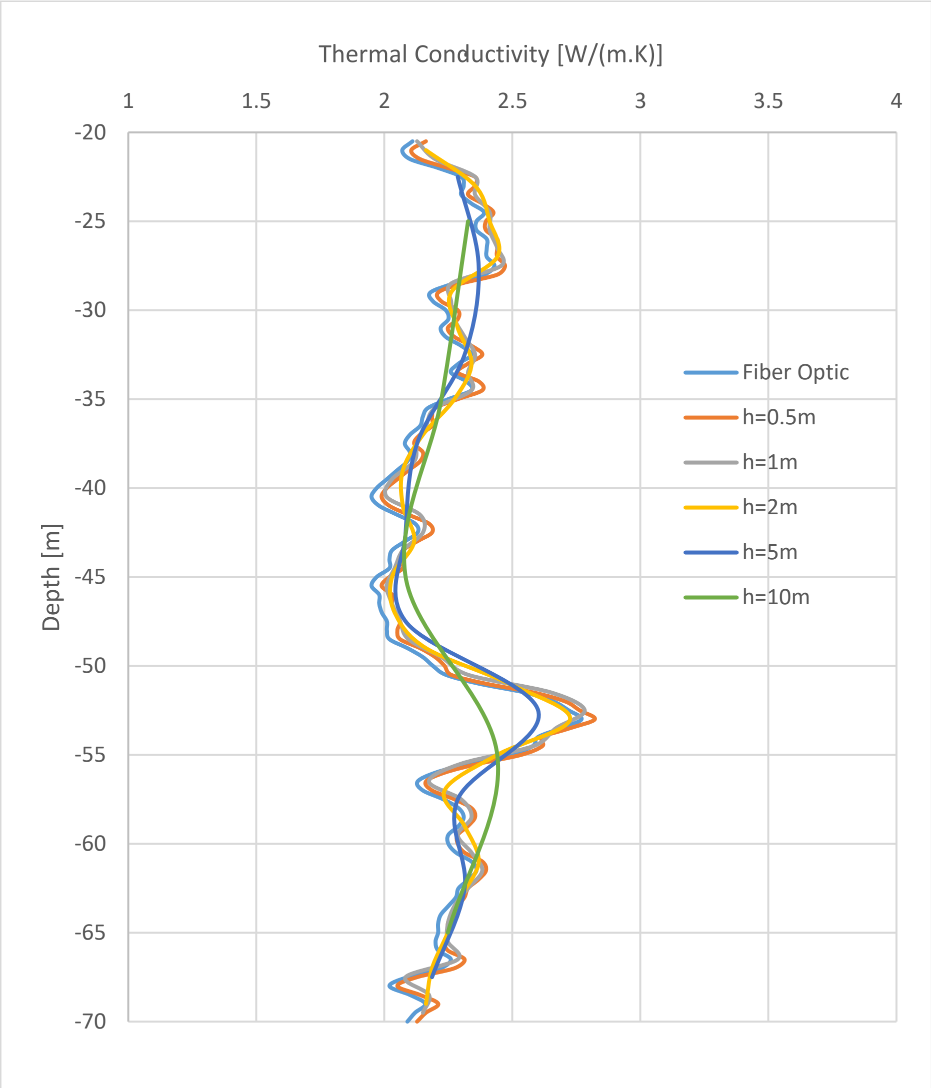

Figure 3: Comparison of different discretization in the borehole. Thermal conductivity profiles were obtained by using different discretization.

Besides the thermal conductivity, the heat fluxes that required to be given to the borehole in order to keep constant temperature are important. Sensitivity analysis of different discretization is given in the following section.

3.1. Sensitivity Analysis

The decision of which length is the optimum to obtain results in a good accuracy is another important question. In order to investigate this, we analyzed different cases depending of the uncertainty of the heat energy provider of TRTs. In a general heat provider has 5% uncertainty (Witte, 2013). If we apply this uncertainty to the different cases we can see the quality of representation of the discretization. Figure 4 shows heat fluxes for each point in 50. hour in a hypothetical test and for 2 m-section case high and low limits of the heat power. As can be seen if 2 m-section heating is applied very close results can be obtained.

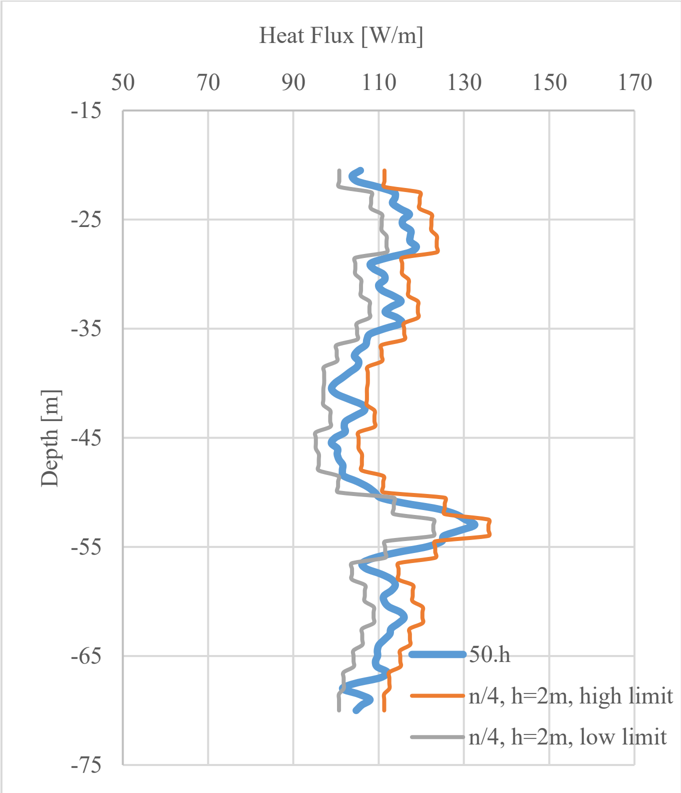

Figure 4: Average heat flux profile in 50.hour and high and low power limits of the heat energy provider in case of 5% uncertainty 2-m heating sections.

If 5m-sections is applied the obtained thermal conductivity profile is given in Figure 5.

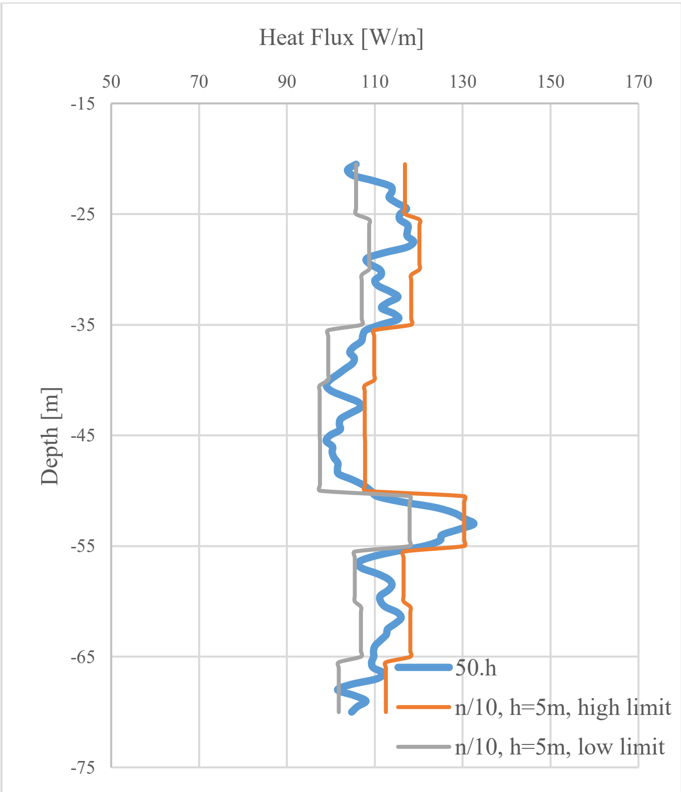

Figure 5: Average heat flux profile in 50.hour and high and low power limits of the heat energy provider in case of 5% uncertainty for 5-m heating sections.

If 10m-sections is applied the obtained thermal conductivity profile is given in Figure 6.

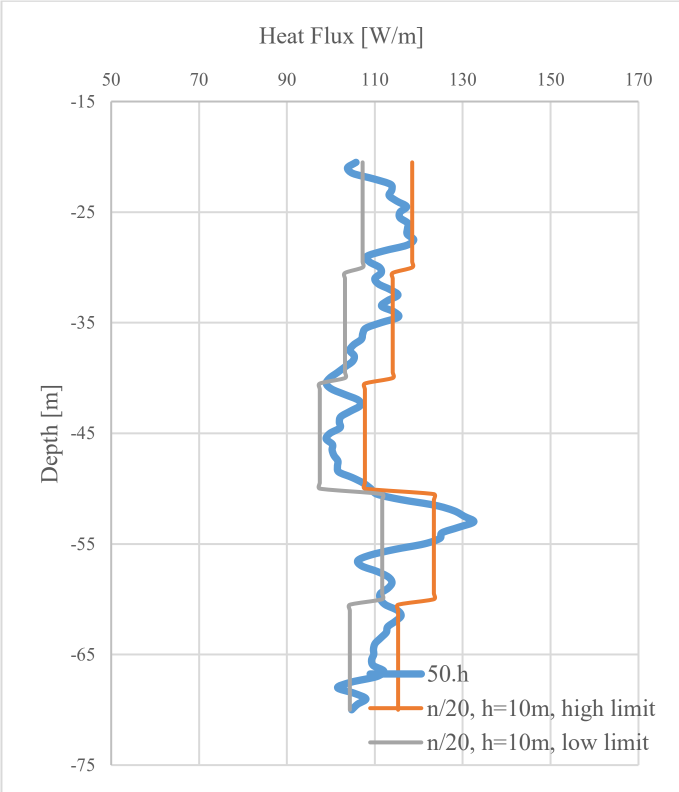

Figure 6: Average heat flux profile in 50.hour and high and low power limits of the heat energy provider in case of 5% uncertainty for 5-m heating sections.

Standard deviations of average values of the 5-m sections and 10-m sections are around 6 % same because of high deviation around the -55. m.

3.2. Investigation of convection in water column

If constant heat flux is applied to a section, because of the different thermal conductivities of through the section, small temperature changings can be observed in the water column. If hot fluid exists in the lower part of the column, due to the its lighter density it wants to move up to the upper part and similarly, if cold water exists in upper part then it wants to move down to the lower part. By this effect, some circle type convection cells may be observed in a water column (Berthold, 2010). The convection cells in the column will occur only if the local Rayleigh number is higher than the critical Rayleigh number. In a cylindrical fluid column, the Rayleigh number can be given as:

$$Ra = \frac{\beta g \Delta T}{\alpha v \Delta z} r^4$$

where β is thermal volume expansion coefficient [1/K], $\Delta T/\Delta z$ thermal gradient [K/m], α thermal diffusivity of water [m^2/s], v is the kinematic viscosity [m^2/s], r is the radius of the water column. The critical Rayleigh number is given by (Gershuni and Zhukhovitskii, 1976)

$$Ra_{cr} = \frac{96}{5(1+7\lambda)}\left[3(33+103\lambda) - \sqrt{3(2567+14794\lambda+26927\lambda^2)}\right]$$

where λ is the ratio of thermal conductivity of fluid to thermal conductivity of surrounding material. General pipe diameters used in U-tubes are DN32 and DN40, and their inner radiuses are 0.0131 m and 0.016 m respectively. Because of the most used one is DN32, here is also it is considered and for this pipe diameter the Critical Rayleigh numbers is obtained as 147.47. If the Rayleigh number exceeds this value, convection cells will be observed for the given conditions here. For this Rayleigh number critical temperature gradient ($\Delta T/\Delta z$) is obtained as 0.131 K/m.

In order to see which points of the borehole exceed the threshold, temperature deviation profile of the water column is drawn for the h=10 m case as is shown in Figure 7.

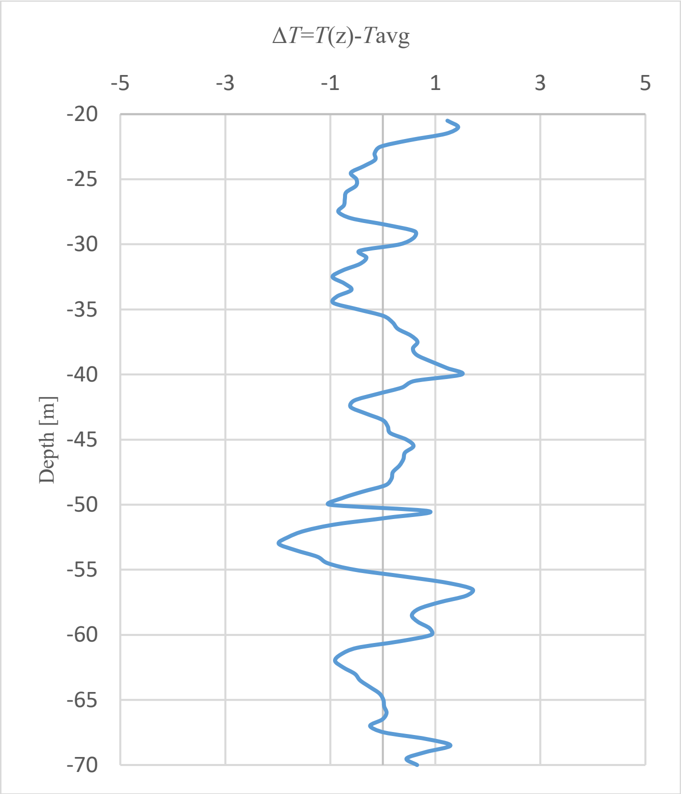

Figure 7: Temperature deviation profile of the water column in the borehole for n/20 (h=10m) case.

Figure 8 shows temperature deviation profile for n/10 (h=5 m) case:

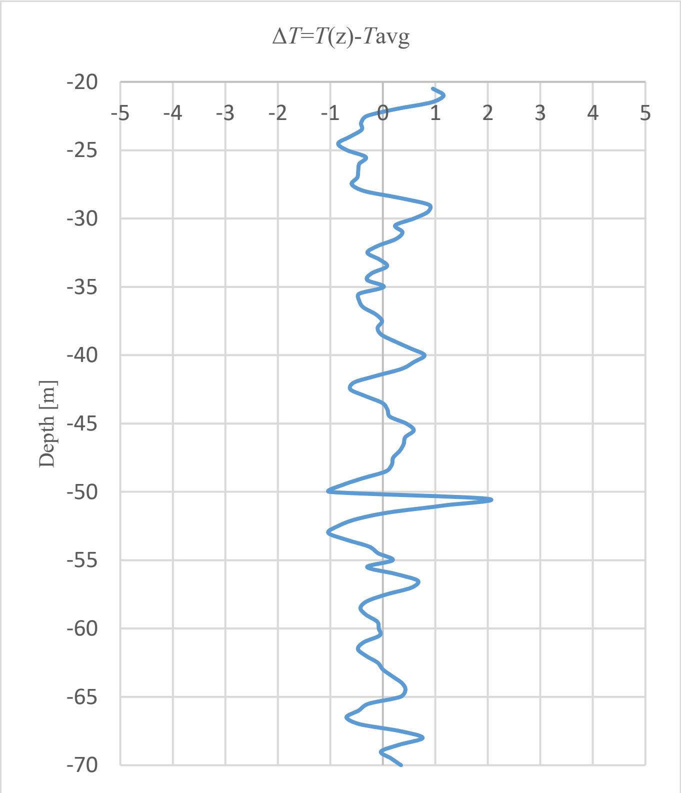

Figure 8: Temperature deviation profile of the water column in the borehole for n/10 (h=5m) case.

Figure 9 shows temperature deviation profile for n/4 (h=2 m) case:

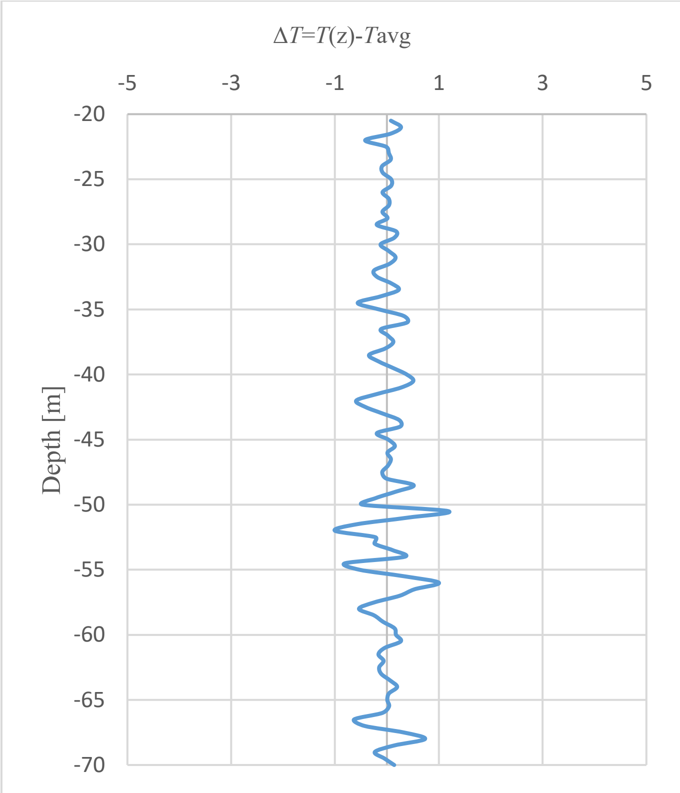

Figure 9: Temperature deviation profile of the water column in the borehole for n/4 (h=2m) case.

In the test, some part of the pipe area is also filled with the probe and the open region that convection takes place decreases. The open area will be similar to horizontal cross-section of a torus and in this case, it is not easy to predict the critical temperature gradient analytically. However, with a probe 1 cm diameter the open area will be decreased with a factor 1.66 and the critical gradient will be equal to approximately 1K/m, that is achieved in the n/4, h=2 m case (Fig.9).

However, if the pipe diameter is wider more intense discretization will be required, if the most part of the pipe diameter will be filled with the probe sparser discretization can be implemented.

4. CONCLUSION

In this study, constant temperature thermal response test with a probe consisting of heating cables and temperature sensors is introduced. The feasibility of the method is investigated with numerically using an experimental data of a borehole whose thermal conductivity is previously known. The considered part of the borehole is divided into different sections and a sensitivity analysis was also carried out depending on different discretization numbers. Moreover, convectional analysis has also shown and the critical Rayleigh numbers are given.

Consequently, it is seen that as the discretization is increased, i.e. if the length of the heating sections is decreased more detailed results can be obtained without exceeding threshold of the critical Rayleigh number and without observing considerable convectional cells. Obviously preparing one probe with one heating section i.e. 1-Layer probe is straightforward, and agglomerate thermal conductivity of the layers can be obtained like in the conventional TRT. However, when the number of the layer is increased, more cables must be added or a special cable must be used. Feasibility of preparing such a test probe cannot be seen in a numerical study. In the following parts of this study, an experimental test will be carried out in a borehole and an implementation of the test can be seen more detailed.

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REFERENCES

Aydin, M., Onur, M. and Sisman, A.: A new method for analysis of constant temperature thermal response tests. *Geothermics*, **78**, (2019), 1-8.

Berthold, S.: Synthetic Convection Log — Characterization of vertical transport processes in fluid-filled boreholes, *Journal of Applied Geophysics*, **72**, (2010), 20–27.

Gershuni, G., Zhukhovitskii, E.: Convective Stability of Incompressible Fluids. Keter Publishing House Jerusalem Ltd, (1976).

Javed, S., Spitler, J.D.: Calculation of borehole thermal resistance. In: Simon, J., Rees (Eds.), Advances in Ground-Source Heat Pump Systems. Woodhead Publishing, (2016) 63–95.

Lamarche, L. Kajl, S., Beauchamp B.: A review of methods to evaluate borehole thermal resistances in geothermal heat-pump systems, *Geothermics*, **39**, (2010), 187–200.

Marquez, M.I.V., Raymond, J., Blessent, D., Philippe, M., Simon, N., Bour, O., Lamarche, L.: Distributed Thermal Response Tests Using a Heating Cable and Fiber Optic Temperature Sensing, *Energies*, **11**, (2018), 3059.

Tombe, B.F., Bakker, M., Smits, F., Schaars, F., Made, K.J.: Estimation of the Variation in Specific Discharge Over Large Depth Using Distributed Temperature Sensing (DTS) Measurements of the Heat Pulse Response, *Water Resources Research*, **55**, (2019).

Wang, H., Qi, C., Du, H., Gu, J.: Improved method and case study of thermal response test for borehole heat exchangers of ground source heat pump system, *Renewable Energy,* **35**, (2010), 727–733.

Witte, H.J.L.: Error analysis of thermal response tests, *Applied Energy*, **109**, (2013) 302–311.

NOMENCLATURE

k_w	Thermal conductivity of water	[W/(m.K)] 0.5918
β	Thermal volume exp. coeff.of water	[1/K], for 40°C, 385 x 10^{-6} [1/K]; for 30°C 303 x 10^{-6} [1/K]
g	Gravity acceleration	[m/s^2] 9.8
α	Thermal diffusivity of water	[m^2/s] for 40°C : 0.151 x 10^{-6} [m^2/s]; for 30°C: 0.148 x 10^{-6} [m^2/s]
v	Kinematic viscosity of water	[m^2/s] for 40°C : 0.6579 x 10^{-6} [m^2/s], for 30°C : 0.8007 x 10^{-6} [m^2/s]
Ra_{cr}	Critical Rayleigh Coefficient	
Ra	Rayleigh coefficient	
λ	ratio of the. cond. to fluid therm. cond.	k_i / k_w
z	depth	[m]
T	temperature	[°C]
T_∞^n	undisturbed ground temp. for n case	[°C]
$T_{\infty i}$	undisturbed ground temp. of *i*. layer	[°C]
k_i	thermal conductivity of *i*. layer	[W/(m.K)]
T_{test}	test temperature	[°C]
r	radius of pipe	[m]
r_{eq}	equivalent radius	[m] calculated using the multipole method
m_i	slope of 1/q_i' in log. time scale	[m/W/cycle]
γ	Euler's coefficient	0.5772