Experimental measurement and long term predictions of a multi-U tube borehole performance for ground source heat pumps

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Abstract: In vertical ground source heat pump applications, usually a single-U tube is used in a borehole. In some studies, double U-tube is suggested to improve the heat transfer rate per unit length of borehole. Therefore a cost and performance analysis for multi U-tube applications in a borehole is needed to determine the net benefit. In this study, a triple U-tube is inserted in a 50m borehole. Heat transfer rate per unit length of the borehole is experimentally measured when single, double and triple U-tubes are in operation separately. Experimental measurements showed that increment of number of U-tubes in a borehole increases performance of the borehole considerably. The relation between number of U tubes and heat transfer rate per unit length is analyzed. Long term borehole performance predictions are made and compared for single, double and triple U tube applications.

Key Words: Borehole heat transfer rate, borehole performance improvement, multi U-tubes

1 INTRODUCTION

One of the obstacles on growing of ground source heat pump (GSHP) market is the initial cost of GSHP systems, despite the operational cost of the system is lower. Especially in vertical applications, drilling of a borehole is quite expensive. Horizontal piping is cheaper than vertical ground heat exchanger (GHE) but it requires big application area and its performance as not good as vertical ones. Decrement of the cost depends on increment of heat transfer rate per unit borehole length (unit HTR value). To increase heat transfer from the ground, some solutions are developed. Some studies have been focused on increasing thermal conductivity of materials (Allan 1999, 2000, Koyun et al. 2009). There are also some works on improvements of GHE (Zarrella et al. 2013, Zanchini et al. 2010, Fujii et al. 2012, Congedo et al. 2012). At the first years of GSHP applications, one U-tube was widely used in a borehole. Later, designers tried double U-tubes in one borehole and some authors notified that performance of GHE increases 20-25% in case of double U-tubes (Banks 2008, Florides et al.2012). For a long time, double U-tubes are using in one borehole with great ability.

There are some significant studies on the performance comparison of multi U-tubes. In the study of Florides (2012) it has been shown that, in series connection for double U-tube give better results than single U-tube while parallel connections give quite high results for a short time operation. First triple U-tube applications has been used in foundation piles. In study of Park et al. (2012), W type and triple U-tube ground heat exchanger has been examined experimentally and numerically for the application in foundation piles. They used thermal response test (TRT) for 72 hours and found that triple U-tube application gives better performance than W type for a short operation conditions. However, for long operation time, longer borehole length than the foundations' length is necessary as they mentioned in their paper. The other significant study have been done by Zarrella (2013). They investigated helical-pipe and triple U-tube in foundation pile with 12m depth and they found that helical pipe application is 9% better than triple U-tube foundation applications.

However foundation applications have different properties: Their boreholes are wider diameter and shallower depth than the conventional boreholes and they can be effected by weather changes. Beside this, the usage of helical-pipe is quite harder in a deep boreholes.

In a deep borehole, more than two U-tubes can be used easily and efficiently. In this study, unit HTR values are investigated experimentally when the number of U-tubes in a borehole changes from one to three. Similar to double U-tube, triple U-tubes can be used in a deep borehole by using special spacers. In this study, triple U-tubes is used in a single borehole to see difference between the performance of single, double and triple U-tubes. It may be better to use three different boreholes with different number of U-tubes for a comparison. However it is nearly impossible to provide the equality of the conditions of boreholes. Because of that, in this study, the same borehole is used to see just the effect of number of U-tubes on unit HTR value of a borehole.

2 EXPERIMENTAL STUDY

For experimental investigation, a borehole is drilled and triple U-tube GHE is inserted in it (Fig.1). Properties of the borehole are given in Table 1. For drilling, a drilling collar of 0.2m diameter is used (Fig.2a). Before the borehole drilling, triple U-tube GHE is prepared nearby the borehole. To avoid the contact of pipes to each other and prevent thermal short cut in GHE, a special spacer prepared for triple U-tube. (Fig. 2b) Spacer is used at each meter of GHE and they are fixed for stability (Fig.2c). When GHE is prepared and the drilling is finished, GHE is placed inside of the borehole (Fig.2d). For placing down the GHE inside the borehole, a weight is attached at the edge of GHE. Pipes are tested by high pressure water before the grout is filled. As grout, Mix 111 proposed by Allan M.L. is used without bentonit (properties of grout is shown in Table 2).

Table 1: Borehole Properties.

Borehole		
Length	50	m
Diameter	200	mm
U-tube		
Number of U-tubes		3
Material		PE100
İnner diameter	26.6	mm
Outer diameter	32	mm
Thermal Conductivity	0.4	W/mK
Borehole-laboratory piping		
Borehole-laboratory distance	15	m
Insulation thick	9	mm
Grout		
Thermal Conductivity	2.19	W/mK

Pipes from the GHE are connected to the test system at the laboratory. This connection line is 0.5m depth from the surface. Each inlet and outlet pipes carried to laboratory separately. Connection pipes between the borehole and the test system are insulated by elastomeric rubber insulation.

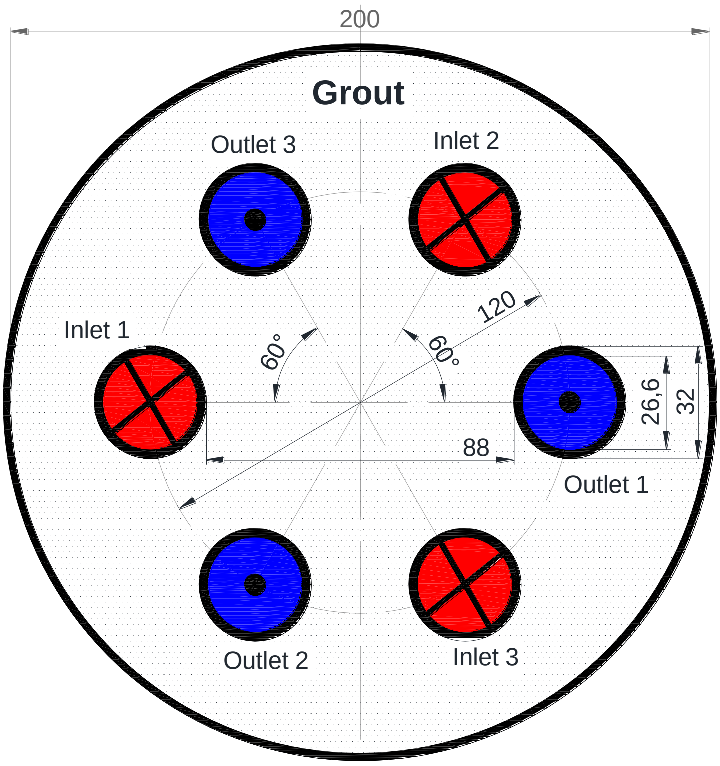


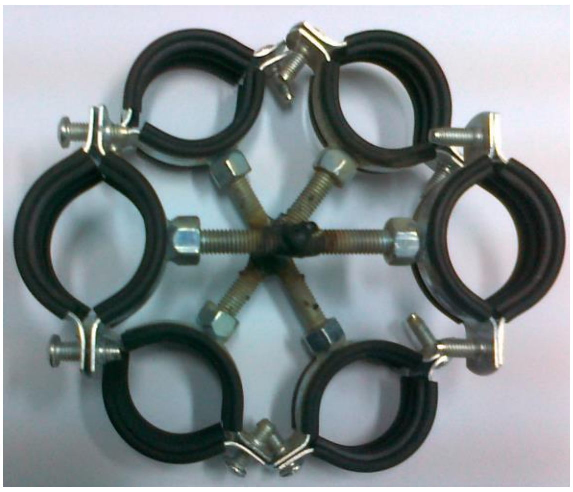
Figure 1: Cross Section of Borehole

After the pipes are connected Thermal Response Test (TRT) system, air inside the pipes is automatically purged.

3 THERMAL RESPONSE TEST METHOD

For predicting the performance (HTR value) of the borehole, thermal conductivity and thermal diffusivity of the ground is experimentally determined by TRT. For many years, TRT is applied under constant heat flux condition and called as constant heat flux method. Another method is the constant temperature method, CTM. CTM has some important advantages like better accuracy, shorter time to achieve steady state regime and wide range of operating temperature, etc. although test system is more expensive due to its temperature control need. In this study, CTM is used due to its advantages.

a)



b)

c) d)

Figure 2: a) Drilling collar, b) Spacer, c) Spacer used per GHE meter, d)GHE in the borehole

Flow rate, inlet and outlet temperatures are measured and recorded in real-time for each pipe by PT1000 temperature sensors and liquid turbine flow-meter. Properties of temperature sensor and flow meter are given in Table 3. Temperature sensors are calibrated in a calorimetric container to get the same results from each sensor for the temperature range of from 2 ^{0}C and 55 ^{0}C. Flow-meters are also calibrated by Siemens Mag5000 flow-meter.

Table 2

Grout Proportion		
Cement	0.5	kg
Sand (Quartz)	1	kg
Superplasticizer	7	ml
Water	0.26	lt

Constant temperature TRT system mainly consist of a water tank, electrical resistances in it, hydraulic circulating pump, PID control unit, data logger. (Fig. 3 and 4)

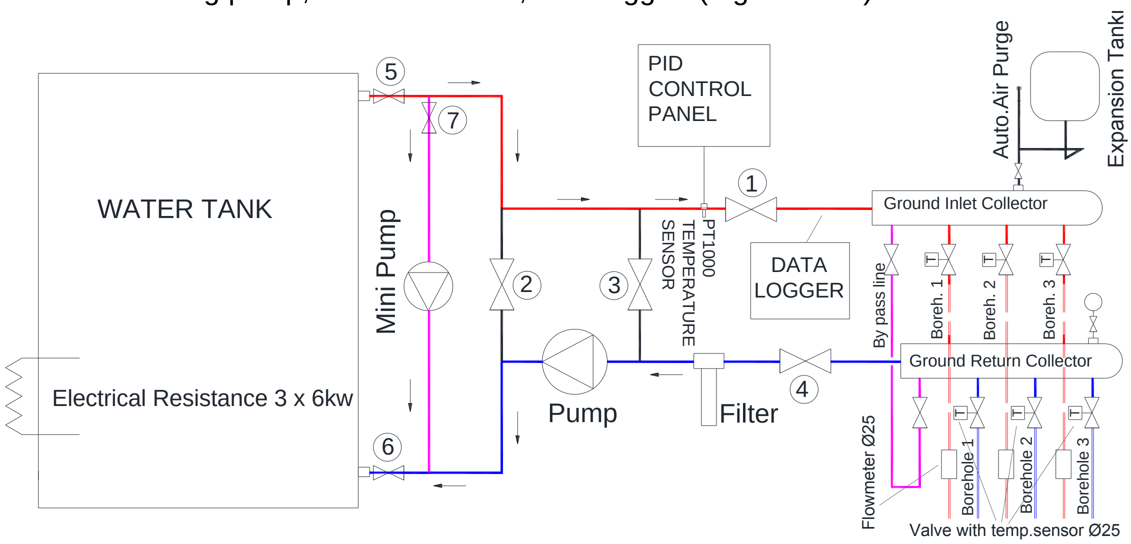


Figure 3: Constant Temperature TRT System

By this system, each U-tube can be tested separately and also test time can be longer to get more accurate results.

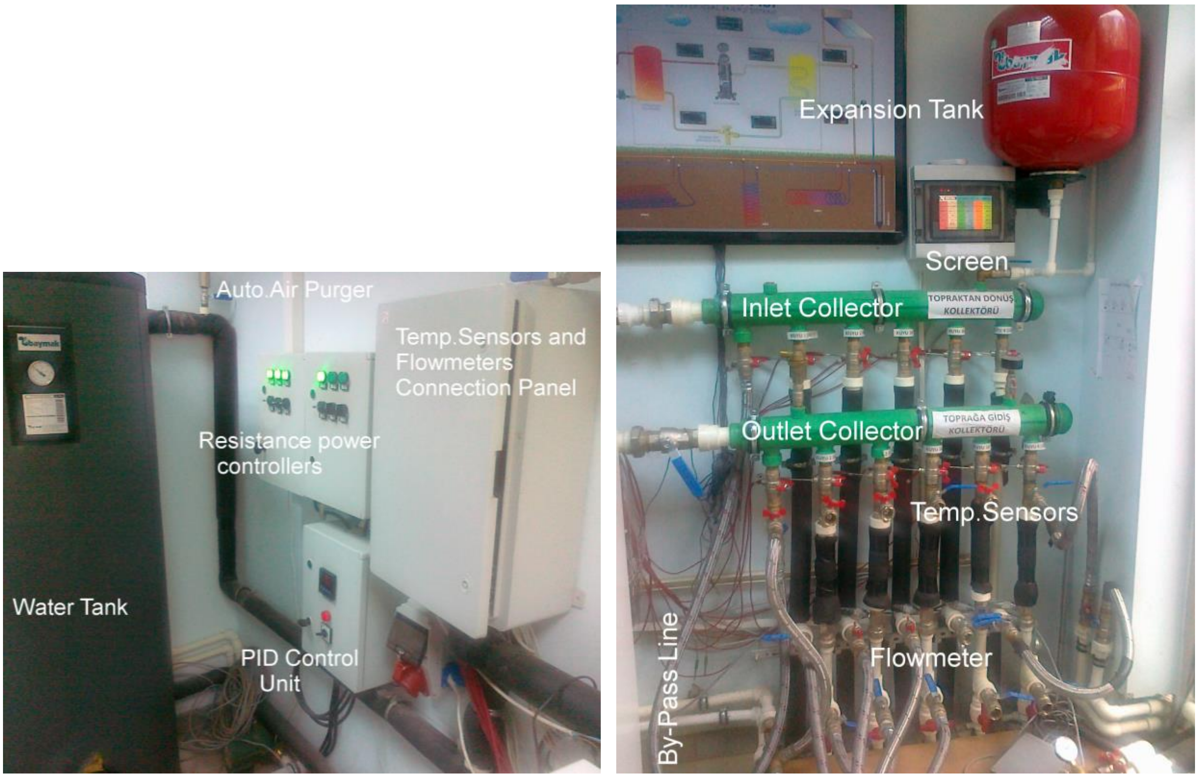


Figure 4: Thermal Response Test System Pictures

After the air purged from the system, undisturbed ground temperature has to be measured before the test is stared. By closing the valves 3,5,6,7 in Fig. 3 and running the pump, circulating water temperature after 15-20 minutes gives the information about the undisturbed ground temperature as in Gehlin (2002). Later, valves 2, 3, 7 and borehole's valves are closed, mini pump and electrical resistances with PID control are run to heat the water in the tank up to test temperature (40 ^{0}C). When the tank temperature achieved to test temperature, by-pass line and valves 2 and 3 are closed, valve 7 is half opened and the others are fully opened, and then test is started. Mini pump on the tank provide homogeneity of tank temperature. Inlet temperature is measured and controlled by PID controller.

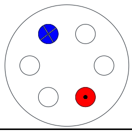
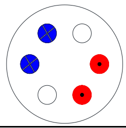
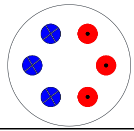
Table 3: Specifications of Flow-meter and Temperature Sensors

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

4 TEST RESULTS

Tests are done between 2th of September and 27th of November 2013. First, single U-tube is tested. After the test, the borehole left alone to recover the initial undisturbed ground temperature for two weeks. Undisturbed ground temperature measurements verified the recovering. Then, double U-tube is tested, and again two weeks are given for recovering. Finally triple U-tube is tested. Test times are 70h for each test. Test results are given in Table 4.

Table 4: Test Results

			1U-Tube	**2U-Tube**	**3U-Tube**
Specifications	**Symbol**	**Unit**			
Total Flowrate	$\dot{V}$	lt/min	16.1	31.9	47.4
Fluid velocity in pipes	v	m/s	0.482	0.478	0.474
Average Fluid Inlet Temp.	T_{in}	^oC	40.0	40.0	40.0
Average Fluid Outlet Temp.	T_{out}	^oC	35.8	37.4	37.9
Undisturbed Ground Temp.	T_{∞}	^oC	17.0	17.2	17.3
Ground Temp. at z=-0.5m	$T_{z=-0.5m}$	^oC	25.2	22.3	18.4
Total Heat Transfer Rate	$\dot{q}_{total}$	W	4715	5784	6941
Heat loss borehole to lab.	$\dot{q}_{loss}$	W	185	478	900
Borehole heat transfer rate	$\dot{q}$	W	4530	5306	6041
Unit heat transfer rate	$\dot{q}'$	W/m	**90.6**	**106.1**	**120.8**
% difference in unit HTR with respect to 1U tube			**0**	**17.1**	**33.4**

Test temperature is chosen as 40 ºC Flow velocity is 0.48 m/s. Heat transfer rate of GHE is calculated by;

$$\dot{Q}_{total} = \dot{m} C_p (T_{in} - T_{out}) . \qquad (1)$$

Because temperatures are measured in the laboratory instead of at top of the borehole, heat loss from the pipes between borehole and laboratory should also be considered. Since inner and outer temperatures of the pipes, properties of pipe materials and insulation and pipe lengths are known, this loss is simply calculated by

$$\dot{Q}_{loss} = \frac{(T_1 - T_3) L}{\dfrac{\ln(r_2/r_1)}{2\pi k_{Pe}} + \dfrac{\ln(r_3/r_2)}{2\pi k_{Ins}}} . \qquad (2)$$

where k_{Pe} and k_{Ins} are thermal conductivities of polyethylene pipe and insulation materials respectively, L is the length of the pipes between borehole and laboratory, T_3 is assumed to be equal to the ground temperature at 0.5m deep from the surface which is given in Table 4 for each case. Pipe and insulation thicknesses are given in Fig. 5;

Therefore heat transfer rate of borehole is easily determined by

$$\dot{Q} = \dot{Q}_{total} - \dot{Q}_{loss} \qquad (3)$$

During this calculation of heat losses, each pipe is assumed to be surrounded by soil, but in real application, pipes touch each other and they will interact thermally (Fig.6), therefore real heat losses are even lower than the calculated heat losses given in Table 4.

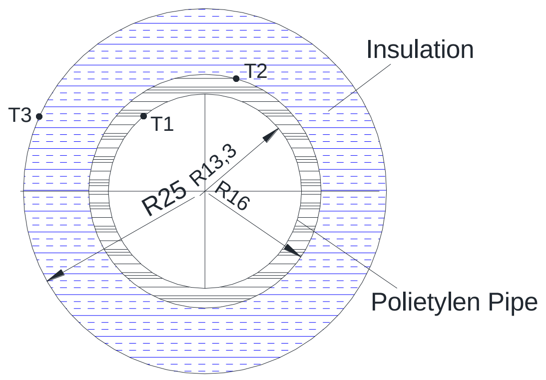


Figure 5: Cross Section of Pipe Between Borehole and Test System

Figure 6: Connections between Borehole and laboratory before close the trench

Variation of the measured unit heat transfer rates versus time for all three cases are shown in Figure 7.

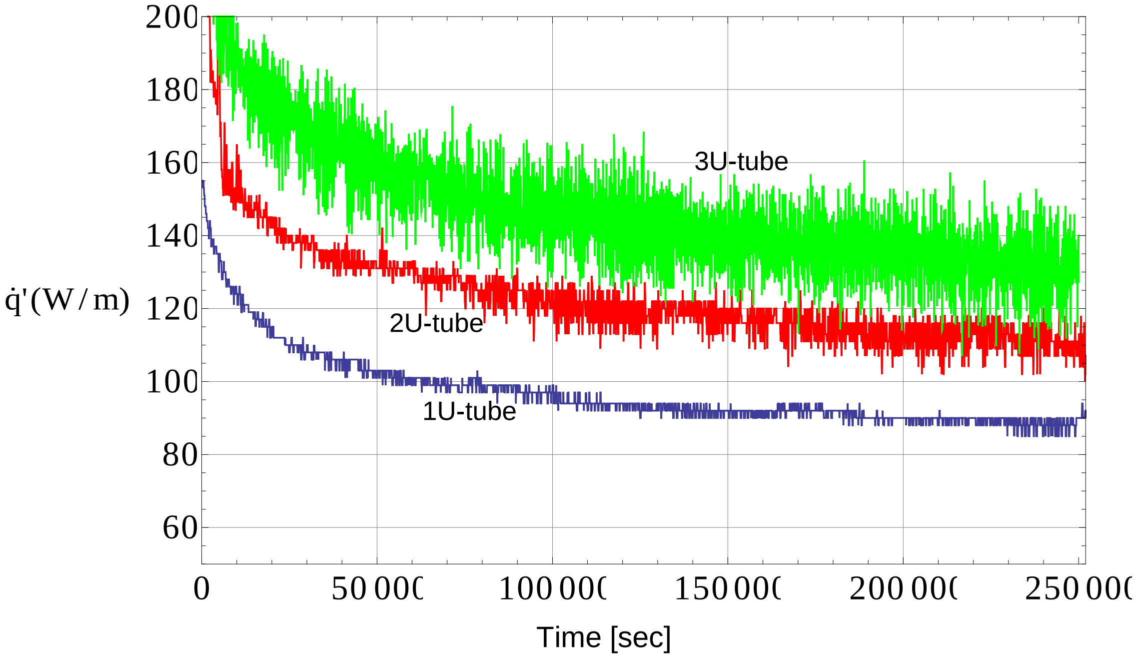


Figure 7: Test Results

To make the long term predictions for unit HTR values, a mathematical model derived under assumption of homogenous ground properties is used, Aydin (2013). Unit HTR value is analytically given by

$$\dot{q}'(t) = 4k(T_0 - T_\infty)\int_{\beta=0}^{\infty} \frac{e^{-\beta^2 \alpha t/r_b^2}\left[Y_0(\beta)J_1(\beta) - J_0(\beta)Y_1(\beta)\right]}{\beta\left[J_0^2(\beta) + Y_0^2(\beta)\right]} d\beta \quad (4)$$

where T_0 is the borehole wall temperature T_∞ is undisturbed ground temperature, r_b is radius of borehole, k and α are thermal conductivity and diffusivity of the ground respectively. Equation (4) is fitted to the experimental data obtained during thermal response tests to determine thermal conductivity and diffusivity of the ground. Fitted curves are shown as dashed, bulleted and solid lines in Figure 8a, 8b and 8c respectively.

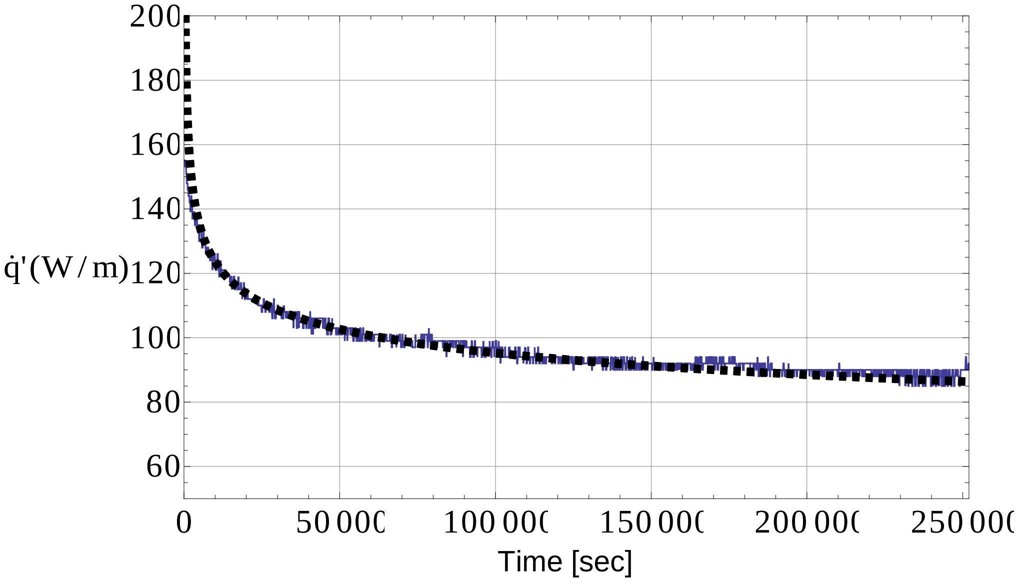


Figure 8a: 1U-tube test results and the fitted curve

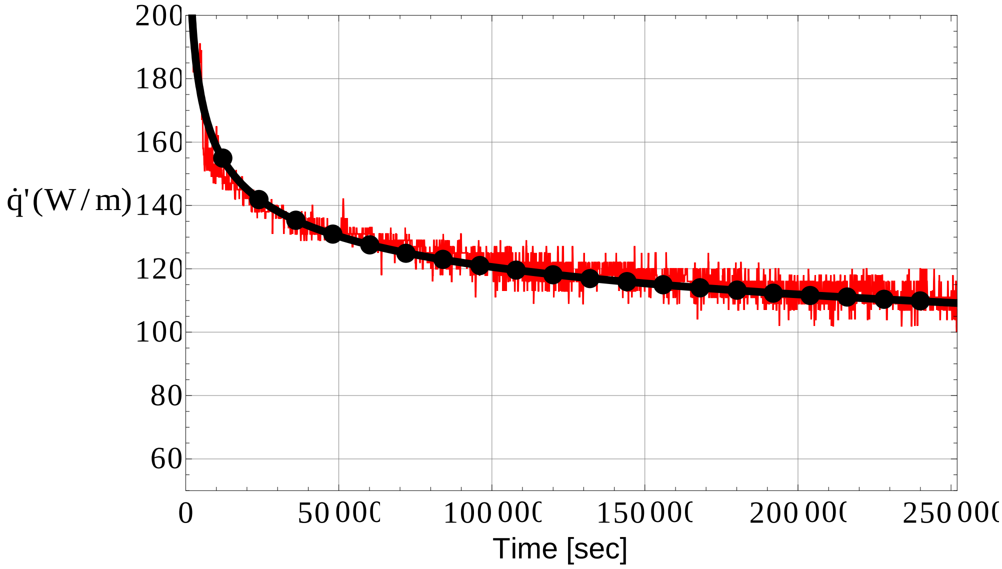
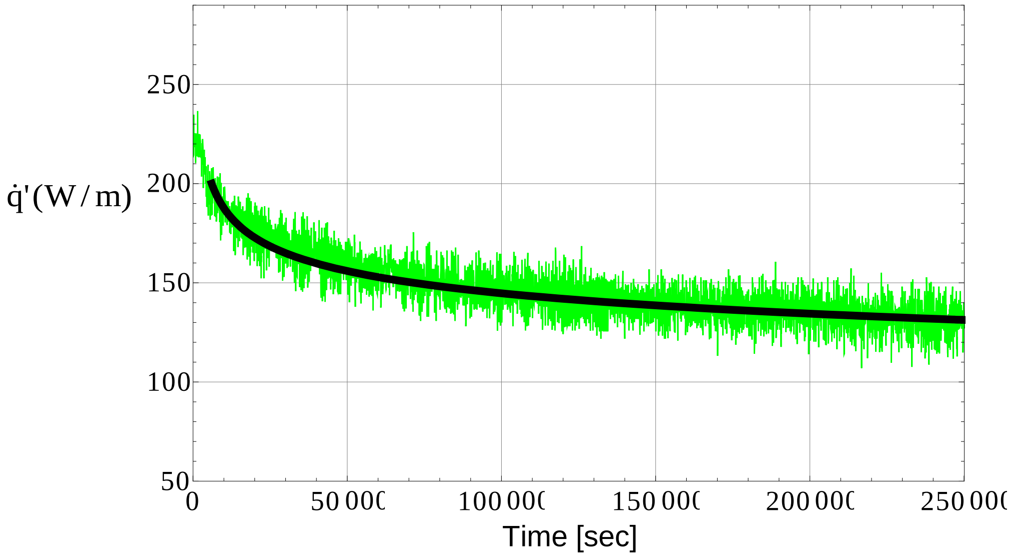


Figure 8b: 2U-tube test results and the fitted curve



c)

Figure 8c: 3U-tube test results and the fitted curve

A comparison of all the fitted results is given in Fig.9.

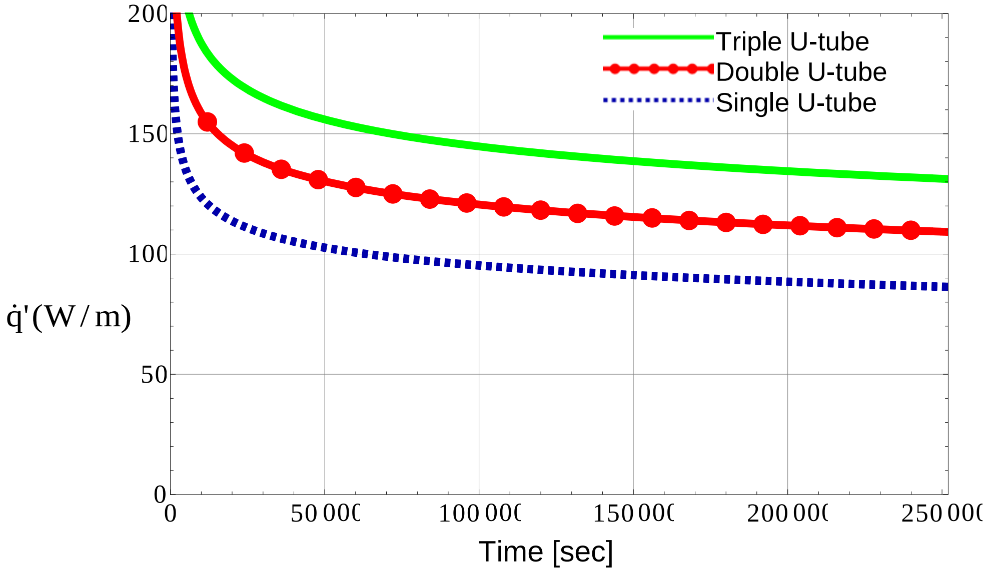


Figure 9: A comparison of fitted results for 1U, 2U and 3U tubes borehole

In Figure 9, a comparison of three cases is shown during test time (70h). For triple U-tubes, unit heat transfer rate goes to around 127 W/m, while it goes 107 W/m for double U tubes and 92 W/m for single U tube at end of the tests. It shows that double U tubes 17% and 3U tubes 33% better than single U tube application.

Although test duration is limited by 70h, long term predictions of three cases can be made by Equation (6) after it is used to determine thermal conductivity and diffusivity of the ground by considering test data.

Figure 10 shows long term (16 weeks) predictions of unit HTR values for three cases. These values are obtained in case of continuous working of borehole. Actual ground heat exchanger system does not work 24h a day, instead, it starts and stops all the day depending on the demand of the building. Because of that, under the real working conditions, unit HTR values will be even better than in Fig. 10. In other words, results in Fig. 10 represent the worst case results which can be helpful for designing a reliable system.

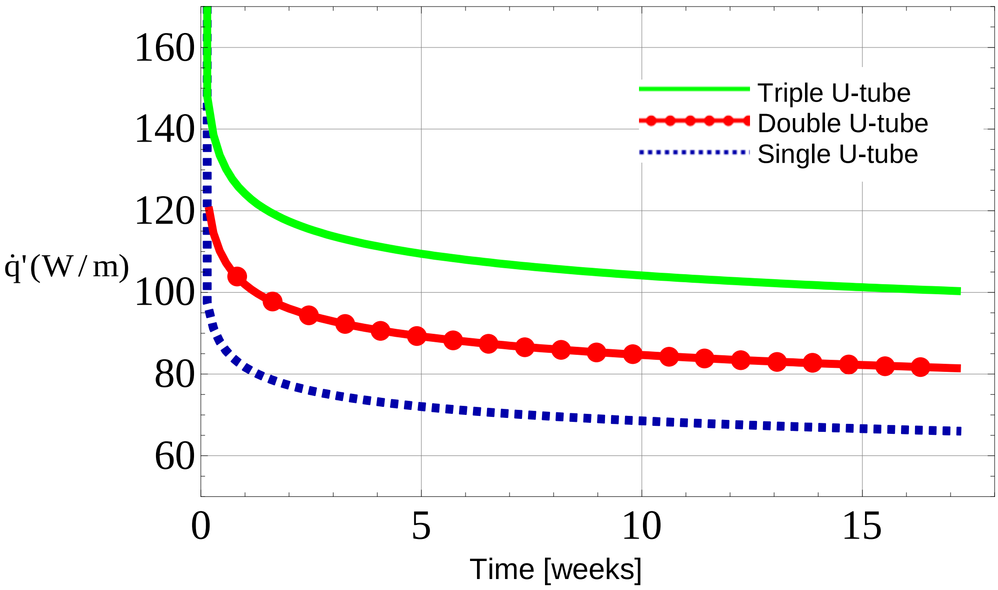


Figure 10: Long time prediction of unit HTR values of a borehole with 1U, 2U and 3U tubes

5 CONCLUSION

In this study triple U-tube is used in a single borehole and its performance (unit HTR value) is experimentally compared with those of double and single U-tubes. The results show that double U-tube has 17%, triple U-tube has %33 better performance in comparison with that of a single U tube. It can be said that in a borehole it is better to use more U-tubes as much as it can. Since the cost of drilling of a borehole is one of the main parts of total cost, drilling cost can be reduced up to 25%. In other words, instead of drilling four boreholes with single U-tube, it is possible to drill three boreholes with triple U-tubes. Therefore, a considerable cost reduction can be achieved by using triple U-tube boreholes. On the other hand, temperature decrement rate at the near region of borehole will of course be higher in case of triple U-tube application in comparison with single U-tube applications. Therefore, this situation should be considered during the determination of optimal distance between the boreholes as well as recovery time for a borehole to get the initial undisturbed ground temperature.

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