AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF SOME DESIGN AND OPERATIONAL PARAMETERS ON HEAT TRANSFER RATE PER UNIT BOREHOLE LENGTH

Ahmet Gultekin, Murat Aydın, Altug Sisman, Istanbul Technical University, Energy Institute,34469 Maslak/Istanbul/Turkey
Sukru Dincer, Can Erdoğan, BDR Baymak Makine Sanayi ve Ticaret A.S. Orhanlı Beldesi, Orta Mh., Akdeniz Sk.No:8 Tepeoren Mevkii, Orhanlı Tuzla, 34959, Istanbul/Turkey

Abstract: Borehole cost is an important part of the total cost of a ground source heat pump system. Optimization studies to increase the heat transfer rate per unit borehole length (unit HTR value) can decrease the cost and make the system more feasible. Therefore, in this study, the effects of borehole depth, flow velocity, pipe diameter as well as the space between the pipes on unit HTR value are experimentally investigated. Unit HTR values of 50m and 100m boreholes are compared. Similarly three different flow velocities are used during the experiments to show the effect of flow velocity on unit HTR values. Pipes of 32mm and 40mm diameter are used in boreholes to investigate the effect of pipe diameter on unit HTR values. Two different spaces (97 mm and 120 mm) between the axes of the pipes (shank space) are considered and unit HTR values are measured. Moreover, last two cases are also modelled by COMSOL Multi-physics software environment to make some further analyses. Experimental results are discussed to obtain higher unit HTR values.

Key Words: ground source heat pumps, borehole heat transfer rate, borehole parameters

1 INTRODUCTION

Ground Source Heat Pumps (GSHPs) have received significant attention in recent years, because of their high energy efficiency. The most common method to exchange heat with the ground in GSHP systems is by means of U-tube Borehole Heat Exchangers (BHE) installed boreholes. Drilling of a borehole is an expensive application, because of that reason design and operational parameters, which could effects unit HTR value, must be chosen carefully.

For this purpose, there are some computational and a few experimental studies for U-tube applications. The work by Hellström et al. (1998) presents a 3D temperature field around a U-tube and useful values for borehole thermal resistance of a single U-tube as a function of borehole filling material for three different pipe positions in the borehole. The effect of pipe spacers, which keep the distance between the pipes constant, on HTR value has been experimentally investigated at Oklahoma State University (Nash 1998). Another finite element method analysis presented by Esen et al. (2009) shows that thermal shunt flow between pipes becomes larger for deeper boreholes. Some experimental and computational works by Acuña et al. (2008, 2009) and Ten (2008) illustrate that the position of U-tube in a borehole can also effect the unit HTR values. Acuña et al. (2013) made experimental investigations for different volumetric flow rates, the results show that decreasing volumetric flow rate causes an increment of temperature difference between the pipes therefore increases the thermal shunt flow.

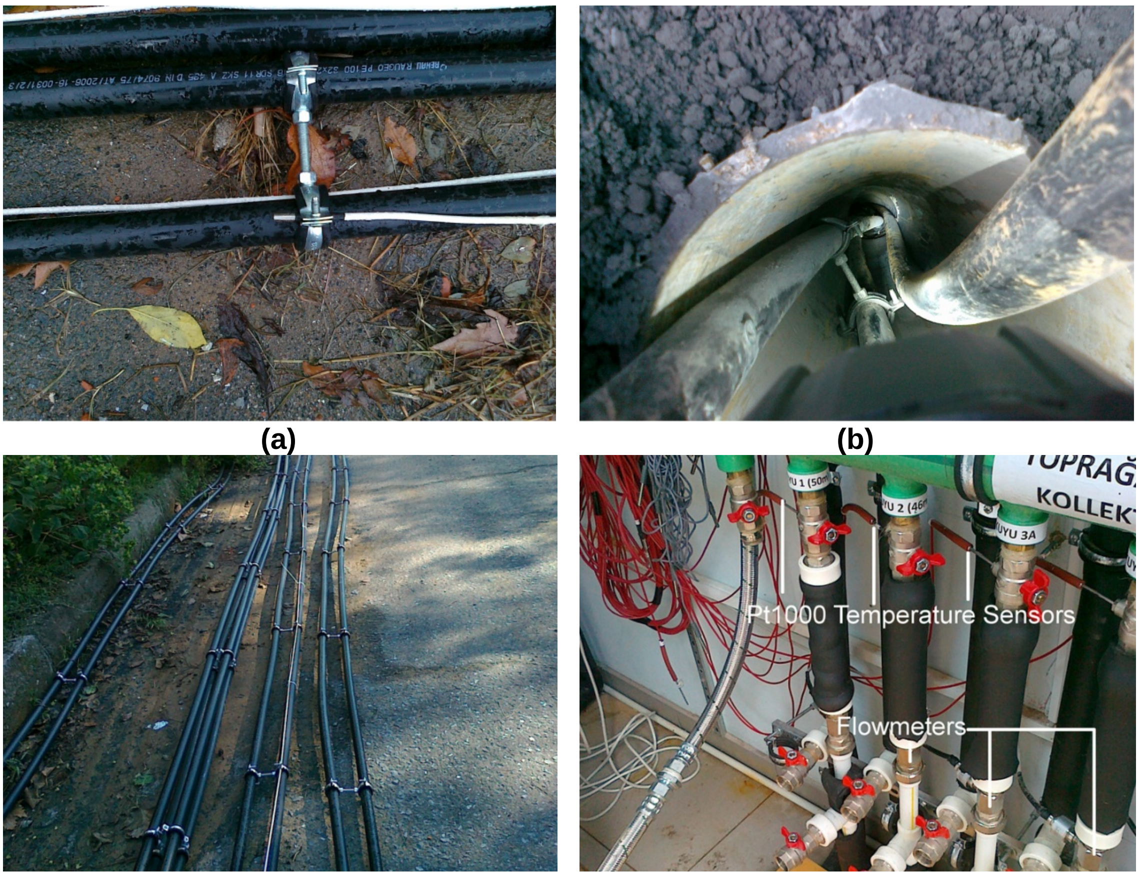
In this study, the effects of borehole depth, flow velocity, pipe diameter as well as the space between the pipes on unit HTR values are experimentally investigated. Afterwards, effects of pipe diameter and shank space on unit HTR values are calculated by COMSOL Multi-physics to examine them independent of borehole diameter since borehole diameters are different in some experimental setups.

2 EXPERIMENTAL INVESTIGATIONS

For experimental investigations a number of boreholes are drilled in the field close to the laboratory. Properties of the boreholes are given in Table 1. To prevent contact of pipes each other and avoid thermal shunt flow in BHE, a special spacer prepared for U-tubes (shown in Figure 1a). Spacers are used each meter of BHE and they are fixed for stability. When BHEs are prepared and the drilling is finished, BHEs are installed inside the borehole, (shown in Figure 1b.) When installing the BHEs inside the borehole, an extra weight is used to putting down easily. Pipes are tested at high pressure with water before the grout is pumped into borehole. Grout Mix 111 proposed by Allan, M. et al., (2000) from Brookhaven National Laboratory is used.

Table 1: Design Parameters for Boreholes

PARAMETERS	BOREHOLE1	BOREHOLE2	BOREHOLE3	BOREHOLE4
Length [m]	50	100	50	50
Inner Diameter [mm]	26.2	26.2	32.6	26.2
Outer Diameter [mm]	32	32	40	32
Shank Space [mm]	97	97	97	120
Borehole Diameter [mm]	176	176	200	200



(c) (d)

Figure 1: (a) Spacer, (b) Borehole inside, (c) PE Pipes, (d) Measurement System

Polyethylene pipes from BHE to the laboratory are insulated with elastomeric rubber insulation and buried to the ground at 0.5m depths.

U-tube BHEs are the most common method to exchange heat with the ground. In most cases, high density flexible polyethylene pipes with dimensions of 40x3.7 and 32x2.9 are used. Their thermal conductivity is around 0.38 W/(m*K). Polyethylene pipes offer durability for long lifetime and low cost (Figure 1c).

To see the effects of some design parameters on unit HTR value, constant heating-temperature method is performed, Wang et al., (2010) and Aydın M. et al., (2013). The electrical heating system is able to keep the temperature of a 500 L water tank constant during the experiments. Thus it guarantees the stable inlet fluid temperature to the BHE. The maximum heating power is 18 kW. The heating system is controlled by a PID device. To ensure the homogenous temperature distribution inside the water tank, a mini circulating pump is used to pump the water from top to bottom of the tank.

Inlet and outlet temperatures are measured by Pt1000 temperature sensors which have ± 0.15 K sensitivity. Also flow rates in each BHE are measured by flow meters which have 0.5 % sensitivity (Figure 1d). All values of each sensor are real time monitored and recorded. To control the flow velocity inside the BHE pipes, a multistage pump is used.

2.1 Effect of borehole depth on unit HTR value

Two boreholes having different depths (50 m and 100 m) are considered while the other parameters (pipe diameter, shank space, borehole diameter and volumetric flow rate) are the same to examine the effect of borehole depth on unit HTR value. Inlet temperature and flow rate of circulating fluid inside BHE are 40^{o}C and 0.265 l/s respectively. The test duration is 120 hours, average outlet temperatures of fluid and unit HTR values are given in Table.2

Table 2: Operational Parameters for Investigating Borehole Depth

	Borehole Length [m]	**Volumetric Flow Rate [l/s]**	**T_{in} [^{o}C]**	**T_{out} [^{o}C]**	**q'_{avg} [W/m]**	**Difference [%]**
Borehole2	100	0.265	40.0	32.7	80.9	0
Borehole1	50	0.265	40.0	36.0	88.7	9.6

According to the experimental results, 50 m borehole has approximately 10% high unit HTR value in comparison with that of 100 m borehole. The main reason of this difference is higher thermal shunt value in 100 m borehole due to high temperature difference and longer flow time in borehole. It seems that two 50 m boreholes give more heat transfer performance in comparison with that of a single 100 m borehole. On the other hand, nearly double application field is needed if 50 m boreholes are preferred instead of 100 m ones. Another important issue is the distance between boreholes. If this distance is kept shorter, then the negative interaction between boreholes decreases the HTR values of boreholes. Therefore the distance between boreholes should not be shortened.

2.2 Effect volumetric flow rate on unit HTR value

The same borehole is used for different flow rates (0.149 l/s, 0.265 l/s and 0.447 l/s) to investigate the effect of flow rate on unit HTR value. Inlet temperature is 40^{o}C while the flow rates are chosen as 0.149 l/s, 0.265 l/s and 0.447 l/s during the experiments. Test period of each experiment is 120 hours. Average outlet temperatures of fluid and unit HTR values are given in Table 3.

As shown in Table 3, three times increment in volumetric flow rate causes 15.4% increment in HTR value of 50 m borehole. An increment in volumetric flow rate (or flow velocity) decreases the temperature difference and flow time inside borehole. Therefore it decreases the thermal shunt between the pipes and increases HTR values. On the other hand, higher volumetric flow rates needs more hydraulic power and causes more electrical energy consumption. Thus determination of flow rate is an optimization problem of whole system for a designer.

Table 3: Operational Parameters and Results for Different Flow Velocities

	Volumetric Flow Rate [l/s]	Flow velocity [m/s]	T_{in} [^oC]	T_{out} [^oC]	q'_{avg} [W/m]	Difference [%]
Borehole1	0.149	0.277	40.0	33.5	81.0	0
Borehole1	0.265	0.492	40.0	36.0	88.7	9.5
Borehole1	0.447	0.828	40.0	37.5	93.5	15.4

2.3 Experimental and computational investigation of effect of pipe diameter on unit HTR value

Two boreholes having different pipe diameters (40 mm and 32 mm) and borehole diameters (200 mm and 176 mm) are given in Figure 2. Other parameters like shank space, borehole depth and volumetric flow rate are the same in both boreholes. To eliminate the effect of the difference in borehole diameter on unit HTR value, a computational model in Comsol environment is used. Inlet temperature and flow rate of circulating fluid inside BHE are 40^{o}C and 0.265 l/s respectively. The test duration is 120 hours, both computational and experimental results for average outlet temperatures of fluid and unit HTR values are given in Table.4.

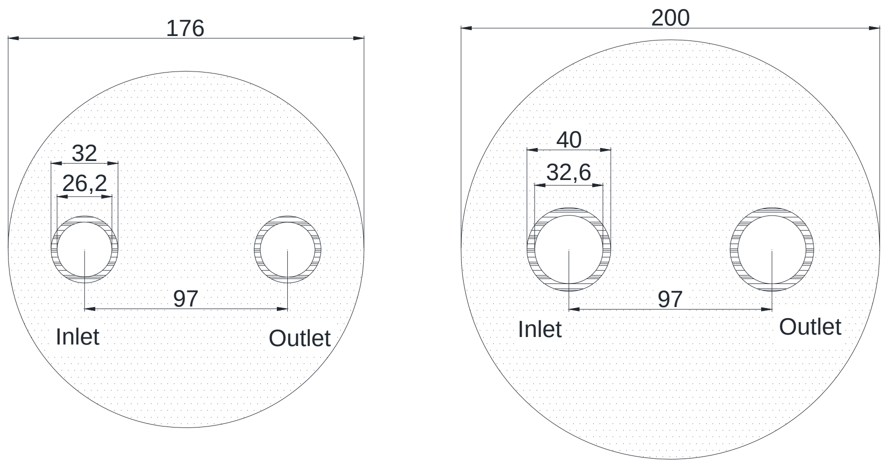


Figure 2: Dimensions of boreholes for investigation pipe diameters

According to the experimental results given in Table 4, increments in both borehole and pipe diameters cause 3.8% increment of HTR value (90.9 W/m and 87.6 W/m). To verify accuracy of the computational model, experimental results are also compared with the computational ones in Table 4. It seems that the accuracy of computational model is quite good. Therefore, computational model can be used to analyze the effects of pipe diameter and borehole diameter on unit HTR values separately. The properties and working conditions used in the model are summarized in Table 5.

With respect to the computational results given in Table 6, 40 mm pipe diameter has better results around 3% than that of 32 mm pipe diameter for both different borehole diameters. To determine the effect of borehole diameter on HTR value, solutions could be compared. It seems that small diameter borehole give slightly more heat transfer performance (2%) in comparison with that of large diameter borehole. Therefore, it could be better to take borehole diameter relatively smaller for the same shank space. In conclusion, neither pipe nor borehole diameters has no significant effect on unit HTR value.

Table 4: Comparison of Computational Results with the Experimental ones

						Exp. Results	**Comp. Results**	
	Pipe diameter [mm]	**Borehole Diameter [mm]**	**Flow rate [l/s]**	T_{in} **[°C]**	T_{out} **[°C]**	q'_{avg} **[W/m]**	q'_{avg} **[W/m]**	**Difference [%]**
BoreH1	32	176	0.265	40.0	36.1	87.6	88.7	1.2
BoreH3	40	200	0.272	40.0	36.0	90.9	89.3	1.6

Table 5: Properties of Solid Materials and Working Conditions for Models

SYMBOL	**VALUE**	**QUANTITY**
Thermal properties of Polyethylene		
k_{pe}	0.38	*Thermal conductivity [W m^{-1}K^{-1}]*
c_{pe}	1900	*Specific heat capacity [Jkg^{-1}K^{-1}]*
ρ_{pe}	958	*Density [kg m^{-3}]*
Thermal properties of grout		
k_{gt}	2.2	*Thermal conductivity [W m^{-1}K^{-1}]*
c_{gt}	750	*Specific heat capacity [Jkg^{-1}K^{-1}]*
ρ_{gt}	1500	*Density [kg m^{-3}]*
Thermal properties of ground		
k_{gd}	2.4	*Thermal conductivity [W m^{-1}K^{-1}]*
c_{gd}	750	*Specific heat capacity [Jkg^{-1}K^{-1}]*
ρ_{gd}	2000	*Density [kg m^{-3}]*
Working conditions		
T_{gd}	17	*Undisturbed ground temperature [°C]*
T_{in}	40	*Inlet temperature [°C]*

Table 6: Computational Results for Different Borehole and Pipe Diameters

	Pipe diameter [mm]	**Borehole Diameter [mm]**	T_{in} **[°C]**	T_{out} **[°C]**	q'_{avg} **[W/m]**	**Difference [%]**
Model1	40	200	40.0	36.0	89.3	2.8
Model2	32	200	40.0	36.1	86.9	0
Model3	40	176	40.0	36.0	91.2	2.8
Model4	32	176	40.0	36.1	88.7	0

2.4 Experimental and computational investigation of the effect of shank space on unit HTR value

Two boreholes having different shank spaces (120 mm and 97 mm) and different borehole diameters (200 mm and 176 mm) are given in Figure 3. Other parameters like pipe diameter, borehole depth and volumetric flow rate are the same in both boreholes. To eliminate the effect of difference in borehole diameter on unit HTR value, the same computational model is used. Inlet temperature and flow rate of circulating fluid inside BHE are 40°C and 0.265 l/s respectively. The test duration is 120 hours, both computational and experimental results for average outlet temperatures of fluid are given in Table 7.

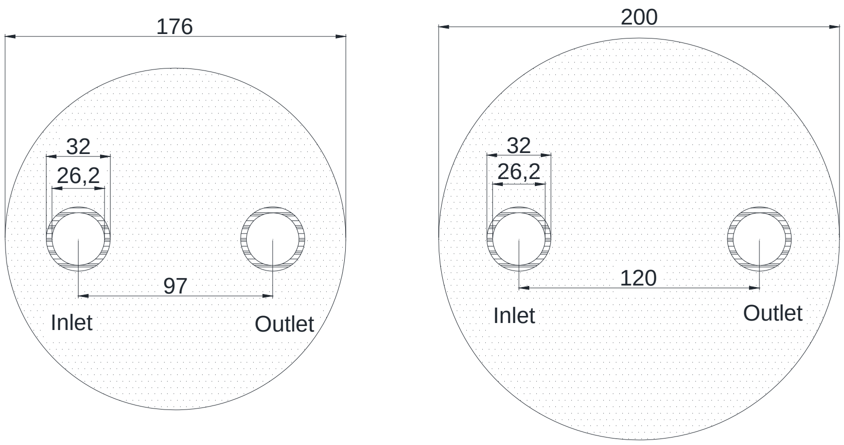


Figure 3: Dimensions of Boreholes for Shank Space Investigation

Table 7: Comparison of Computational Results with the Experimental ones

						Exp. Results	Comp. Results	
	Shank space [mm]	Borehole Diameter [mm]	Flow rate [l/s]	T_{in} [^oC]	T_{out} [^oC]	q'_{avg} [W/m]	q'_{avg} [W/m]	Difference [%]
BoreH1	97	176	0.265	40	36.1	87.6	88.7	1.2
BoreH3	120	200	0.265	40	36.0	89.8	91.7	2.1

According to the experimental results, borehole with 120 mm shank space has approximately 2.5% higher unit HTR value in comparison with that of 97 mm shank space. To verify the accuracy of the computational model, experimental results are compared with the computational ones in Table 7. Computational model can be used to analyze the effects of shank space and borehole diameter on unit HTR values separately. The properties and working conditions used in the model are summarized in Table 6.

Table 8: Computational Results for Different Borehole and Pipe Diameters

	Shank space [mm]	Borehole Diameter [mm]	T_{in} [^oC]	T_{out} [^oC]	q'_{avg} [W/m]	Difference [%]
Model 1	120	176	40	36.0	95.2	7.3
Model 2	97	176	40	36.1	88.7	0
Model 1a	120	200	40	36.0	91.7	5.5
Model 2a	97	200	40	36.1	86.9	0

The effect of shank space on unit HTR value can be seen in Table 8, wider shank space give 7.3% and 5.5% more heat transfer performance in comparison with that of narrow shank space for small and large diameter boreholes respectively. Comparing the computational results for two different borehole diameters, it could clearly be seen that small diameter borehole gives more unit HTR value.

In addition to the experimental study, unit HTR values for a wide range of shank space from 40 mm to 170 mm are computationally modeled and examined for two different borehole diameters. As it is seen in Figure 4, it is better to keep the shank space wider and close to the borehole wall. This result is in agreement with that of Acuna (2009).

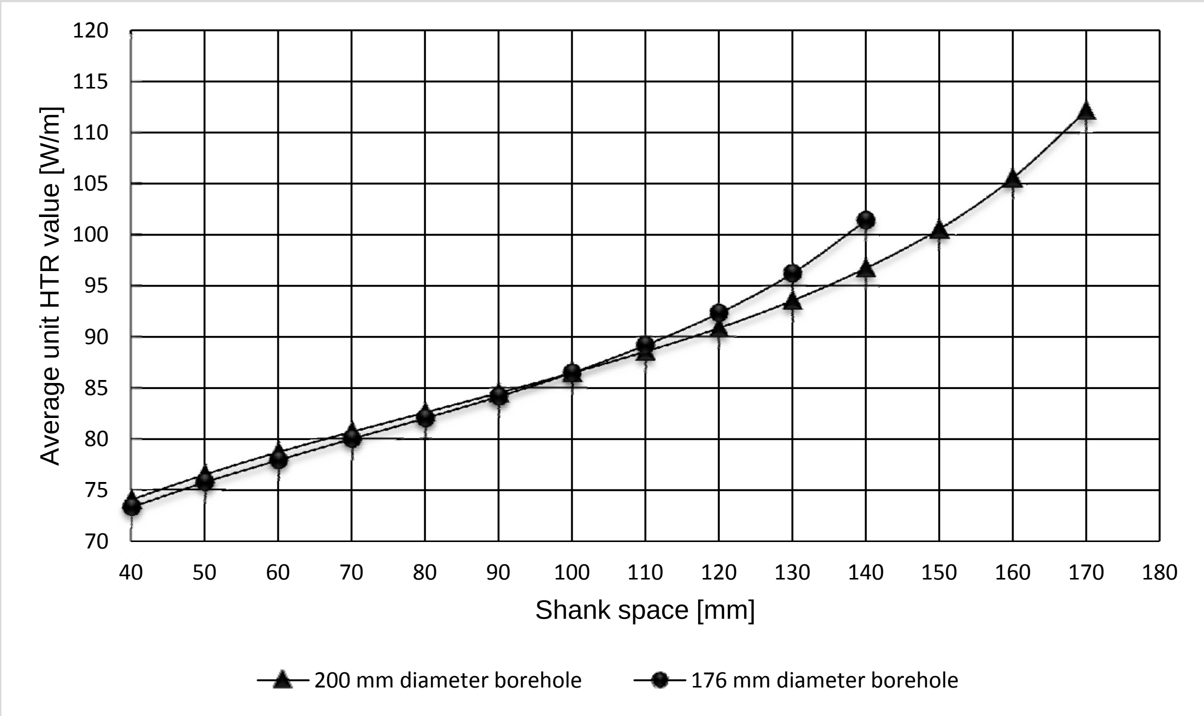


Figure 4: Shank Space Effect on Average unit HTR value in 120 hour period

3 CONCLUSION

The effects of borehole depth, flow velocity, pipe and borehole diameters as well as shank space on unit HTR values are analyzed based on experimental measurements and computational model.

The results show that 50 m borehole has approximately 10% higher unit HTR value in comparison with that of 100 m borehole. The main reason is the higher thermal shunt value in deeper boreholes. Due to the same reason, higher flow velocity value has positive effect on unit HTR value. However electrical consumption of circulation pump should be taken into account for more detailed design calculations. Larger pipe diameter has also positive effect on unit HTR value although the effect is small. On the other hand, wider shank space for the same borehole diameter increases unit HTR values. The results can be used for more efficient and high performance engineering design of GSHP systems.

4 ACKNOWLEDGMENT

This project is supported by SAN-TEZ program of Republic of Turkey, Ministry of Science, Industry and Technology under contract number of 01276.STZ.2012-1.

5 REFERENCES

Acuña José, Palm Björn. (2008) "Experimental comparison of four borehole heat exchangers." 8th IIR Gustav Lorentzen Conference. 7-10 September, Copenhagen, Denmark, 2008.

Acuña José, Palm Björn. (2009) "Local Conduction Heat Transfer in U-pipe Borehole Heat Exchangers". Excerpt from the Proceedings of the COMSOL Conference 10-12 October, Milan, Italy, 2009

Acuña José. (2013) "Distributed thermal response tests – New insights on U-pipe and Coaxial heat exchangers in groundwater-filled boreholes". Doctoral Thesis, The Royal Institute of Technology, Stockholm, Sweden.

Allan, M., Philippacopoulos, A. (2000). "Performance Characteristics and Modelling of Cementitious Grouts for Geothermal Heat Pumps." Proceedings World Geothermal Congress 28 May – 10 June Kyushu-Tohoku, Japan, 2000.

Aydın M., Sisman A., Dincer S., Erdogan C., Gultekin A. (2013) "Toprak Kaynaklı Isı Pompalarında Isıl Cevap Testi ve Kuyu Performansının Analitik Öngörüsü", TESKON 17-20 April, Izmir, Turkey, 2013.

Esen Hikmet, Inalli Mustafa, Esen Yuksel.(2009). "Temperature distributions in boreholes of a vertical ground-coupled heat pump." Renewable Energy [Vol. 34]. pp.2672-2679.

Hellström Göran, (1998). "Thermal Performance of Borehole Heat Exchangers." The Second Stockton International Geothermal Conference 16-17 March, Stockton, USA, 1998.

Nash, R. (1998). U.S. Patent No. 6,000,459.

Ten Maria. (2008) "Thermal Comparison of Two Borehole Heat Exchangers". MSc Thesis, The Royal Institute of Technology, 008:458, Stockholm, Sweden.

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