ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY
February 2020, Vol 13(05), 539 – 551
DOI: 10.17485/ijst/2020/v13i05/148618,

Performance Analysis of Borehole U-tube Heat Exchanger Based on TRNSYS Software

Ala Eldin Mohamed Tairab*, Wei Liu, Ateeq Ur Rehman, Inam Ullah and Kamdem Claude

College of Mechanical and Electrical Engineering, Hohai University, Changzhou Campus, China

Article Type: Article

Article Citation: Alaeldin Muhammad Tairab, Wei Liu, Ateeq Ur Rehman, Inam Ullah. Performance analysis of borehole U-tube heat exchanger based on TRNSYS software. *Indian Journal of Science and Technology*. 2020; 13(05), 539-551. DOI: 10.17485/ijst/2020/v013i05/148618

Received date: November 2, 2019

Accepted date: December 13, 2019

***Author for correspondence:** Ala Eldin Mohamed Tairab terab2017@outlook.com Hohai University, Changzhou Campus, China

Abstract

Background/objectives: There exist many alternatives to store thermal energy for handling the seasonal offset. Among these alternatives, a borehole heat exchanger is better for storage of the thermal energy. **Methods:** In this work, the comparison of the performance of two boreholes U-tube models has been presented. The first one is double U buried pipes and the second one is single U buried pipes with a diameter of 25 mm and 32 mm, respectively. The performance is evaluated by the numerical method and analysis is done by using TRNSYS software. This investigates the thermal functioning of ground heat exchangers by constant inlet water temperatures and different borehole depths. Both single-U and double-U have the same depths but different diameters and sensors of both boreholes are integrated into the circle to measure the temperature. **Findings and novelty/improvements:** The results demonstrate that temperature increases in 105 m depth, this depth of borehole is quite deep. It is also showed that the average thermal conductivity is 1.446 W/m °C; the average thermal diffusivity is 0.730×10^{-6} m^2/s although the optimum velocity range is 0.3–0.6 m/s. Furthermore, the results show that a single U buried pipe with a large space should be used. The distance between buried pipes must be 5 m. Special attention should pay to the backfilling methods, backfilling construction, and backfilling materials of buried pipes.

Keywords: Borehole, Heat Exchanger, Underground Storage, TRNSYS.

1. Introduction

Renewable energy technologies continue to spread through the continuous expansion of life and science. The distribution of renewable energy resources is wider than the imperfect predictable energy resources and the environment is essentially safe and never-ending. One of those renewable energy resources the borehole heat exchanger [1]. So, quite a lot of methods from the auxiliary heat source or borehole heat exchanger have been considered to prevent and dropping the ground temperature. The operation of the system based on underground conditions including a ground-source heat pump (GSHP). It is considered to be a device that is more energy-efficient and is commonly used in heating and cooling house. The heat exchanger systems of the borehole are most prevalent among all types of heat energy stored [2]. The pile systems for geothermal energy can assist to minimize original expenses. Energy piles are based on the mixture of borehole heat exchangers and deep systemic support structures. Energy pile technologies have been recently produced and are increasingly in demand for both forms of the heat exchanger and underground piles of geothermal energy due to their energy efficiency and financial gain [3]. The effectiveness of medium depth borehole thermal energy storage improves with volume but it takes many years to achieve operational capability, and such systems are useful in urban regions due to the low demand for floor space [4].

China is one of the world's most developing countries, and there is too much influence on the planet's stage. However, for every type of energy utilization is no more than 21s of the residential states. In [5] this study, the underground heat storage is applied for the area (323,694 m^2) located in Yanzheng, south China. It has relatively high solar and geothermal and other renewable energy resources. The reason to study the underground source heat pump system is the adaptation of significant energy-saving mechanisms and protection of the environment, which can improve the thermal condition for energy heating demand.

The system operation is settled on the underground circumstances include ground thermal conductivity, groundwater level, and underground temperature. Though excessive or long-term functions can run to reduce the system performance for the GSHP system. For this study, a buried pipe sits; the experiment of deep geothermal physical property was administered. The drilling test of two boreholes was performed, depending on the state of the current study.

2. Literature Survey

Currently, with borehole and reservoirs, the researchers have made many seasonal storage system tests. A great deal of study has also been applied to explain the quality of energy storage. In Ref. [6], the authors suggested a development capability control system in GSHP, using a computer model to evaluate various control methods and techniques to improve the performance of the seasonal process. Some design effects on process efficiency and net power output were proposed by the authors in Ref. [7] to achieve maximum process efficiencies through the consequent incorporation of two-tank energy storage. The result showed that the conductance of a solar receiver has a stronger effect on system performance and the performance of the system is affected by changes in solar radiation and seasonal air temperature.

Moreover, Rad et al. [8] proposed an advanced simulation tool, ground heat energy storage design system to design the borehole thermal storage. Furthermore, the design of the ground heat energy storage system offers a more cost-effective model, with more power than the standard TRNSYS module.

An approach with a broad diameter and a limited duration of the numerical methods in the borehole is proposed in Ref. [9]. It is concluded that the systems' thermal output is not significantly related to pipes geometry. The test showed that the process performance of the system had been affected. Although the authors in Ref. [10] proposed an approach to the heat exchange rates of the different types of vertical heat exchanger using differences in inlet water temperatures and depths of the borehole. The results showed that in terms of heat exchange rates, the temperature difference between the circulating water and the soil around the borehole has a significant influence. A borehole thermal storage system was suggested by the researcher's in Ref. [11] using two different tubes in TRNSYS to perform loading and unloading simultaneously in the same borehole. The results showed that high solar fraction for space heating. Similarly, Xu and Dubljevic [12] provided mathematically modeling state-of-the-art solar thermal systems for seasonal borehole storage, natural differential equations, and hyperbolic energy balance partials using the Cayley method for modeling discrete systems.

Furthermore, a medium-deep borehole thermal storage system is presented in Ref. [13], to analyses the system efficiency. The result showed that the efficiency is increased when the size of thermal storage increased. Moreover, Bezyan et al. [14] proposed an approach to the different control strategies to achieve a high fraction of the solar heating system through the season of storage. The test showed an increase in the solar energy fraction and an increase in the average temperature of the system.

A three pile-based heat exchangers (W-shaped, U-shaped, and 0.4 m pitch-shaped spiral) approach is analyzed in Ref. [15]. The solution shows that the pile-based heat exchanger is the highest of the heat transfer rate and energy output efficiency. While the researchers in Ref. [16] suggested a design of different diameters and tube loops for different borehole heat exchanger stacks. They simultaneously increased the number of loops and the diameter of the pile. The results showed that with large loops of the pipes and large pile diameter, high heat transfer efficiency was achieved. In addition, Lindenberger [17] proposed a mathematical model of pile heat exchangers to improve the efficiency of pile heat exchangers, with determining how relatively important various design parameters for achieving the maximum exchanged energy. They found that maximizing the total heat transfer for the available area on the pipe is the biggest factor in increasing energy efficiency. Raab [18] suggested a plan to develop strategies in China to reduce the cost of storing thermal energy. They incorporated the non-pressurized solar system, and instead of a large storage tank, multiple standard tanks were interconnected. The result showed that a high collection of solar has been increased over time and the efficiency of solar collectors.

3. Methodology

We used a balanced 220 V power supply in this method, such as large voltage variations (more than 5 percent positive or negative) and electrical power that is not more than 6 KW. The experimental equipment's principle of thermal response is closed heating, cooling, temperature, and flow rate. In addition, the quantity and other sensors are integrated into the equipment's operating process. The piping in the measurement instrument is connected to the underground loop of the geothermal heat exchanger. The circulating water pump has moved the fluid to the loop. The fluid is heated by the heater and then flowed through the underground loop to exchange underground rock and soil energy with all the flow rate, temperature, and heating energy of the inlet fluid being measured and recorded. The process is based on collected data using the developed heat transfer model and the empirical parameter correction method. We measured the heat dissipation capacity of the underground heat exchanger in the summer air conditioning refrigeration experiment, and the intake water temperature is controlled at about 25–30 °C. While the recovery of the lower tube time after back-filling is more than 72 hours and the average experiment duration is 48 hours after installation of the experiment instrument.

The horizontal section of the connecting pipe is very short in the winter heating experiment. Often, the measures of insulation are taken and the effect has been ignored.

Isolating material from rubber-plastic with a wall thickness of 20 mm is used. To isolate the connecting pipes from the test bench to the pipes of the ground heat exchanger, to reduce the potential heat loss caused by the connecting pipes. The relationship between the horizontal average temperature and the surrounding rock and soil temperature at infinity is as follows:

$$T_f = T_{ff} + q_i\left[R_b + \frac{1}{4\pi k_s}.E_i\left(\frac{d_b^2 \rho_s c_s}{16 k_s \tau}\right)\right] \tag{1}$$

Where

$$R_s = \frac{1}{4\pi k_s}.E_i\left(\frac{d^2{}_b \rho_s c_s}{16 k_s \tau}\right) \tag{2}$$

K_s: thermal conductivity of rock and soil around the buried pipe (W/m·°C); q_l: heat transfer capacity per unit depth of borehole (W/m); T_f: horizontal mean temperature in pipe circulation (°C); T_{ff}: soil temperature at infinity (°C); R_b: heat transfer and thermal resistance in the borehole (°C m/W); ρ_s: average density of surrounding rock and soil (kg/m^3); and c_s: average specific heat of surrounding rock and soil (J/m^3·°C); τ: time (s).

$$E_i(x) = \int_x^\infty \frac{e^{-s}}{S} dS \tag{3}$$

Where $E_i(x)$ is an exponential integral function and when the time is long enough:

$$E_i\left(\frac{d_b^2 \rho_s c_s}{16 k_s \tau}\right) \approx \ln\left(\frac{16 k_s \tau}{\rho_s c_s}\right) - \gamma \tag{4}$$

γ: is the Euler constant $\gamma \approx 0.577216$

The two test holes back-filling materials are raw slurry at the bottom and raw slurry + sand at the top. Figure 1 shows the experiment's flow chart, which explains the sum of the temperature variance between the temperature of the experiment and the temperature calculated. If the sum is minimum, it gives the final thermal parameter output; otherwise, it modifies the thermal parameters and restarts.

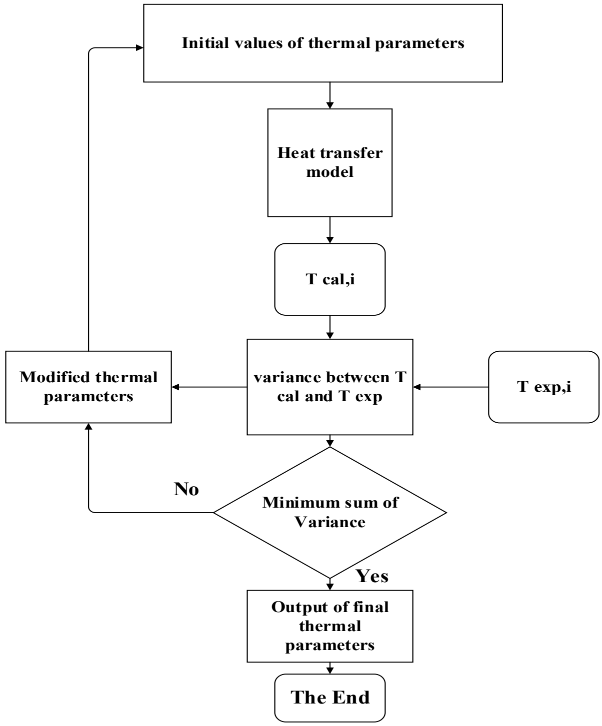

FIGURE 1. Flow chart of the test calculation. T cal: calculated temperature. T exp: experimental temperature.

For this approach, the authors applied a transient simulation software TRNSYS, to study the borehole method. In addition, the borehole system's underground heat pump output was evaluated using TRNSYS as a tool to promote the underground heat pump system performance analysis. The TRNSYS model with the weather data module for reading the typical weather properties, heaters for heating the fluid in front of the borehole, pump for circulating the fluid, storage tanks, parameters for calculating temperatures, controllers, and boreholes. Two boreholes heat pump system is more complicated relative to the independence of the heating system, which increases the corresponding circulation pipeline, heat transfer, and mode of control. The simulation of the heat pump results of the system is completed by changing the setting of the simulation conditions and the parameters. The advantages of the component heat pump system of boreholes are analyzed by simulating the temperature of the water flow rate and power of the model as shown in Figure 2.

4. Results and Discussion

4.1. Ground Temperature

The platinum sensor of resistance temperature with the best performance as the main instrument is used to measure the borehole temperature. All temperature sensors are

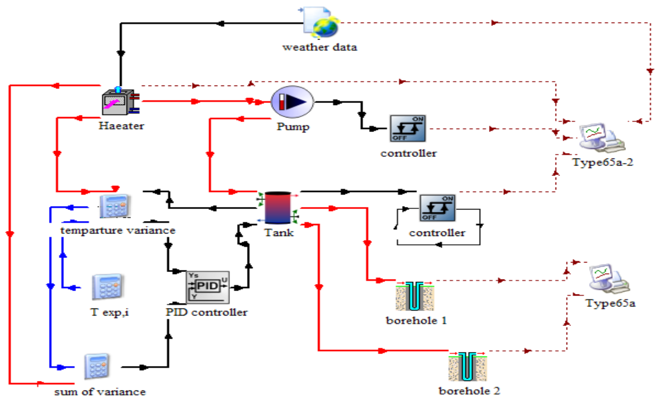

FIGURE 2. Simulation of the borehole using TRNSYS software.

calibrated and the calibration temperature range is 0–40 °C. The sensor error in measuring the inlet temperature and outlet temperature is less than ±0.15 °C. The accuracy of the sensor to test the original soil temperature is 0.01 °C.

Before the buried pipe thermal response test begins, the original soil and rock temperature are first measured with a resistance temperature platinum sensor. The original soil temperature is measured every 5 meters for different depths at a gradient of 0.01 °C. The measurement error is less than ±1% due to flow meters. The maximum range of velocity is 0.3–0.6 m/s.

Figures 3 and 4 show the ground temperature of different depths during a sunny day between the changes in surface and ground temperature. Because of the falling solar radiation on the ground, the soil temperature just below the surface is beginning to heat up and is warmed at a higher rate than the ambient air. The greater soil ability was relative to the ambient air. And as the soil's depth increases the temperature increases too.

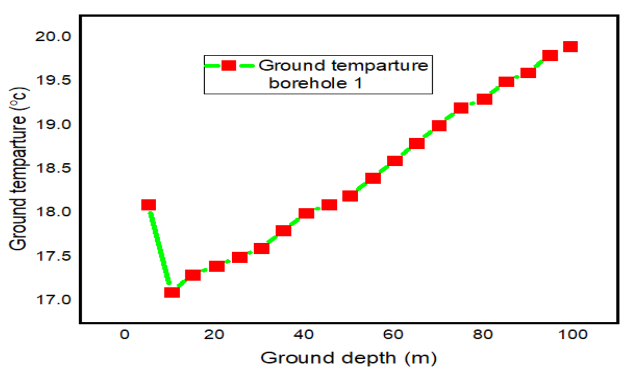

FIGURE 3. The ground temperature of different depths for borehole (1) (double U).

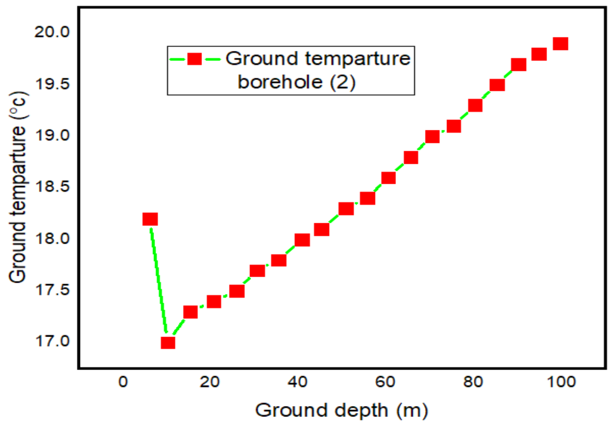

FIGURE 4. The ground temperature of different depths for borehole (2) (single U).

4.2. Calculating and Measuring the Borehole Temperature

The buried pipes are assumed to be arranged symmetrically in the borehole in the heat transfer model adopted in the experiment. The thermal resistance of the borehole is determined, the average distance between the buried pipes and the thermal conductivity of the backfilling material is estimated in advance. It is almost hard to place the buried pipes in the center of the borehole. The average distance between borehole buried pipes is difficult to determine, which makes the tests of the borehole's thermal resistance being more mistakes. In this experiment, most parameters for boreholes, such as the maximum thermal resistance of boreholes, are viewed as an undefined parameter to simplify and prevent error measurement. The transition heating in the buried pipes between flowing water and surrounding soil and rock can be assumed to be the transfer of energy between an infinite linear heat source in the borehole and rock and surrounding soil.

Figures 5 and 6 present the temperature calculating and measuring for borehole (1) and borehole (2), respectively, based on the time using GSHP during the heating process. The temperature calculation is lowest in both boreholes except is higher in the borehole (2) at

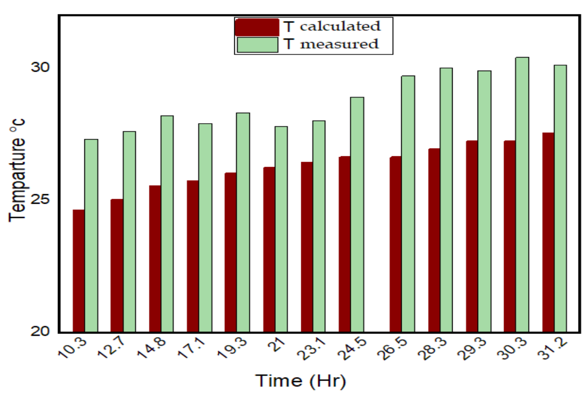

FIGURE 5. Calculating and measuring the temperature of the borehole (1).

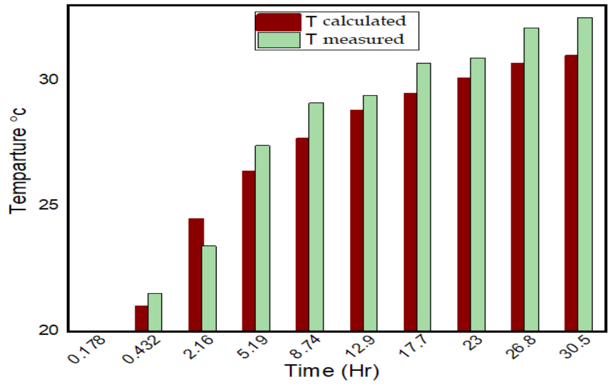

FIGURE 6. Calculating and measuring the temperature of the borehole (2).

the time (2.16 h). It was found that the borehole temperature of the module was influenced by the time and borehole's depth.

4.3. The Buried Pipe Heat Transfer

The initial soil and rock surface temperature are relatively high. Under winter operating conditions, the underground heat exchanger's inlet temperature should be higher than 4 °C, recommending 5–7 °C. In summer operating conditions, the inlet temperature of underground heat exchanger should be no lower than 3 °C. Based on the conditions of the geological region and the properties of the deep rock and soil thermal experiment, the reference suggestions for heat transfer in the underground heat exchanger as shown in Figures 7 and 8.

When the number of buried pipes is too low, the flowing liquid's inlet temperature and outlet temperature are difficult to meet the specifications of the heat pump. As a result, the actual heating capacity of the heat pump is lower than its rated value, that makes the system cannot meet the requirements of the user. On the contrary, if the transfer of heat

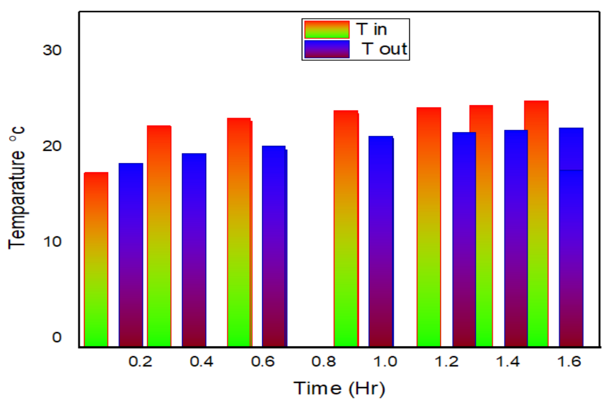

FIGURE 7. The temperature in and temperature out in borehole (1).

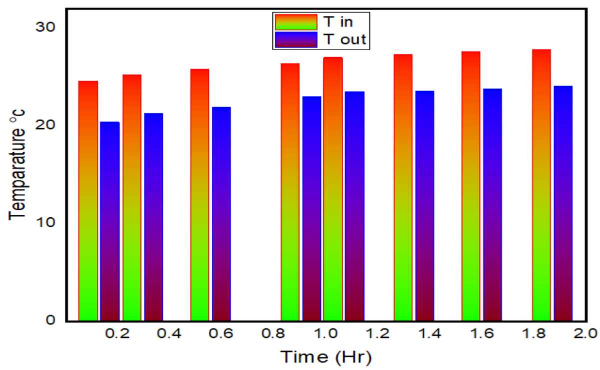

FIGURE 8. The temperature in and temperature out in borehole (2).

per unit hole depth is high, the amount of buried pipe will increase and the initial cost of the project will increase. But the cost unit for operating the heat pump will be reduced. The temperature output of both borehole (1) and borehole (2) based on TRNSYS is shown in Figures 9 and 10.

The result confirmed that the borehole temperature enhanced by time in the first hours and then get constant by time.

4.4. Flow Rate and Time

The findings on both Figures 11 and 12 show that over the most experimental test, the flow rate for boreholes varies significantly. In particular, the system performed well and during the experimental test, no significant hydraulic disturbance occurred. The flow rate measured during the first 3 hours up to 50 hours measurement period is between (15.7 L/min to 16.3 L/min). During the winter period when the air is drier, the influence of evaporation is also more evident. The evaluation shows that the measured flow rates are

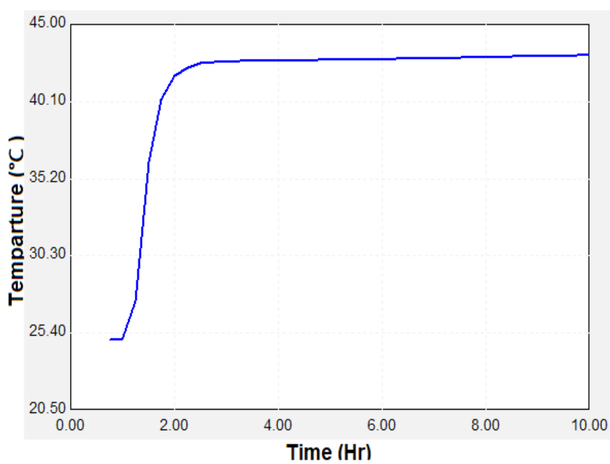

FIGURE 9. Borehole (1) temperature with TRNSYS software.

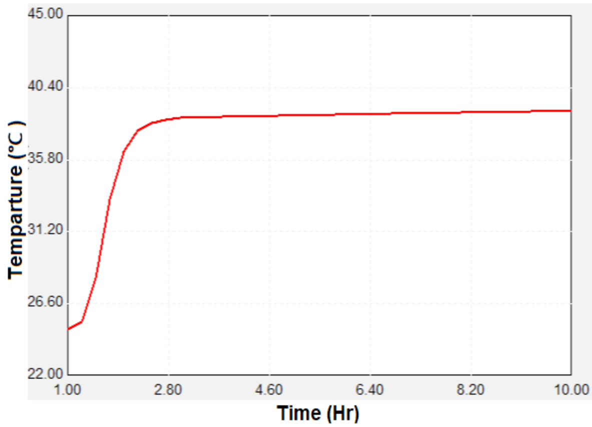

FIGURE 10. Borehole (2) temperature with TRNSYS software.

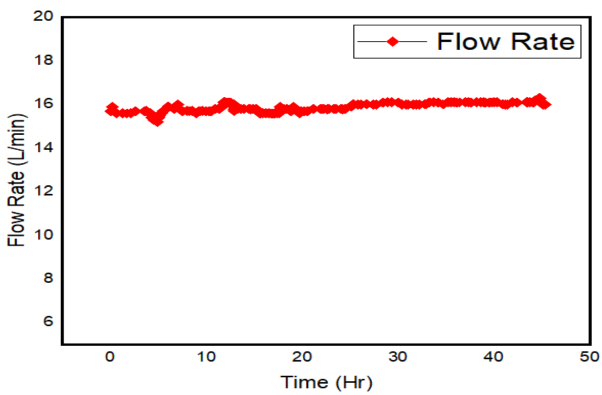

FIGURE 11. Flow rate for the borehole (1).

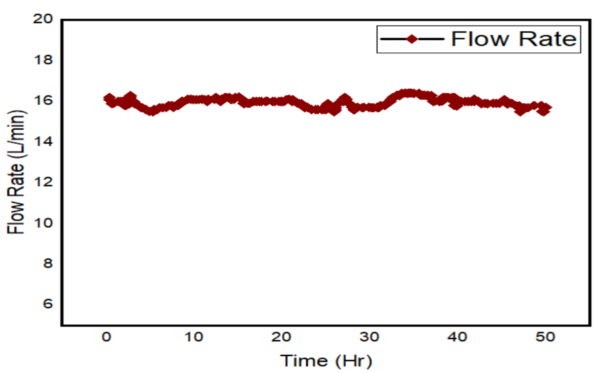

FIGURE 12. Flow rate for the borehole (2).

TABLE 1. The experiment parameters of holes and pipes

Subject	Test hole (1)	Test hole (2)
Drilling depth (m)	105	105
Buried tube form	Double U	Single U
Inner diameter (mm)	20.4	26
Borehole diameter of the buried pipe (mm)	135	135
The external diameter of the buried pipe (mm)	25	32
Buried pipe material	PE100	PE100
Borehole backfilling	Raw pulp + sand	Raw pulp + sand
Major geological structures	Clay + silt	Clay + silt

TABLE 2. The initial average temperature, thermal conductivity, the specific heat capacity of volume of soil in the experiment area and thermal resistance in holes per meter in winter and summer

Subject	Borehole (1)	Borehole (2)	average value
Flow rate (m/s)	0.41	0.5	–
Initial temperature (°C)	18.55	18.48	18.52
Thermal conductivity (W/m °C)	1.566	1.325	1.446
Specific heat capacity ($\times 10^6$J/m^3 °C)	2.102	2.198	2.150
Thermal diffusivity ($\times 10^{-6}$ m^2/s)	0.745	0.714	0.730
Thermal resistance in the hole (m·K/W)	0.051	0.076	0.064

within the range of values measured in each borehole in previous campaigns. Previous borehole measurements gave high flow rates (Table 2).

5. Conclusion and Future Work

The findings of the drilling demonstrated that clay and silt are the main geological factors in the buried pipe region of the borehole. The results of the test showed that the average thermal conductivity is 1.446 W/m °C. The average thermal diffusivity is 0.730×10^{-6} m^2/s, the thermal conductivity, and thermal diffusivity is moderate. The soil layers and rock's thermal physical properties in the experimental area are relatively balanced so that the underground source heat pump system can be applied.

The findings of the simulation-based on distance and number showed that the heat exchanger of the borehole was tested with the same depths and different diameters. All boreholes sensors are built into the circulation process, as well as measuring the heat exchanger's underground heat capacity. While the temperature of the intake of water is monitored at approximately (25–30 °C), the test will last for 48 hours. The borehole depth is 105 m; the effectively buried pipe is 135 m, as well as the soil temperature in different depths, is measured 0.01–every 5 m. Although the optimum velocity range is 0.3–0.6 m/s. The calculated temperature analyzes are lower than measuring temperature and it has been found that the temperature of the borehole module has been affected by the time and depth of the borehole. TRNSYS temperature over time, the borehole temperature is above borehole temperature, the flow rate measured over 5 hours is almost between 15.7 and 16.4 L/min). The average temperature, heat resistance in the hole and the specific heat capacity. The heat extracted or released to the ground from the hole depth per meter in winter for borehole (1) is 41–44 w/m and for borehole (2) is 39–42 w/m. In summer is (51–54 w/m) for borehole (1) and (50–52 w/m) for borehole (2).

It is advised to use single U for buried pipe and the buried pipe should be at a range of 5 m. The diameter of the borehole is deep, and PE100 should be the material of the vertical buried shaft. The structure of the stratum is mostly clay and silt, and it is not very difficult for the borehole. A single U buried tube is proposed to be used for the buried pipe.

- The spacing of buried pipes should be increased appropriately as a means of increasing the regenerator and reducing the underground heat load imbalance when the area of buried pipes is sufficient. It is suggested that the distance of the buried pipe should be 5 m.
- For a long time, if the heat and cold are unbalanced for a long time when using an underground source heat pump for the air conditioning system. The result of heating or cooling is not optimal, so try to keep the balance between heat and cold.
- The methods of backfilling and the backfilling materials of buried pipes should be given special attention. Horizontal pipe welding and connection building, as well as water catchment production and connection.

References

1. Dhakal S, Hanaki K, Hiramatsu A. Heat discharges from an office building in Tokyo using DOE-2. *Energy Convers Manage*. 2004; 45(7–8), 1107–1118.
2. Guadalajara M, Lozano MA, Serra LM. Simple calculation tool for central solar heating plants with seasonal storage. *Solar Energy*. 2015; 120, 72–86.
3. Thompson III, Hope W. Numerical analysis of thermal behavior and fluid flow in geothermal energy piles. Diss. Virginia Tech. 2013; 1–90.
4. Bar K, Ruhaak W, Welsch B, Schulte D, Homuth S, Sass I. Seasonal high-temperature heat storage with medium-deep borehole heat exchangers. *Energy Procedia*. 2015; 76, 351–360.
5. Yue YL, Meng LY, Dong SX, Han SQ. Application of solar central air conditioning system. *Refrigeration Technology*. 2007; (2), 9–12.
6. Madani H, Claesson J, Lundqvist P. Capacity control in ground source heat pump systems: part I: modeling and simulation. *International Journal of Refrigeration*. 2011; 34(6), 1338–1347.
7. Osorio JD, Hovsepian R, Ordonez JC. Effect of multi-tank thermal energy storage, recuperator effectiveness, and solar receiver conductance on the performance of a concentrated solar supercritical CO2-based power plant operating under different seasonal conditions. *Energy*. 2016; 115(1), 353–368.
8. Rad FM, Fung AS, Rosen MA. An integrated model for designing a solar community heating system with borehole thermal storage. *Energy for Sustainable Development*. 2017; 36, 6–15.
9. Bidarmaghz A, Narsilio G, Johnston I. Numerical modeling of ground heat exchangers with different ground loop configurations for direct geothermal applications. Proceedings of the 18th international conference on soil mechanics and geotechnical engineering, Paris, France. 2013, 2–6.

10. Miyara A. Thermal performance investigation of several types of vertical ground heat exchangers with the different operation modes. *Applied Thermal Engineering*. 2012; 33, 167–174.
11. Chapuis S, Bernier M. Seasonal storage of solar energy in borehole heat exchangers. Eleventh international IBPSA conference. 2009; 1–8.
12. Xu Q, Dubljevic S. Modelling and control of the solar thermal system with borehole seasonal storage. *Renewable Energy*. 2017; 100, 114–128.
13. Ur Rehman H, Hirvonen J, Sirén K. Design of a simple control strategy for a community-sized solar heating system with seasonal storage. *Energy Procedia*. 2016; 91, 486–495.
14. Bezyan B, Porkhial S, Mehrizi AA. 3-D simulation of heat transfer rate in geothermal pile-foundation heat exchangers with spiral pipe configuration. *Applied Thermal Engineering*. 2015; 87, 655–668.
15. Cecinato F, Loveridge FA. Influences on the thermal efficiency of energy piles. *Energy*. 2015; 82, 1021–1033.
16. Tao T. Low cost and marketable operational experiences for a solar heating system with seasonal thermal energy storage (SHSSTES) in Hebei (China). *Energy Procedia*. 2015; 70, 267–274.
17. Lindenberger D. Optimization of solar district heating systems: Seasonal storage, heat pumps, and cogeneration. *Energy*. 2000; 25(7), 591–608.
18. Raab S. Validation of a computer model for solar assisted district heating systems with seasonal hot water heat store. *Solar Energy*. 2005; 79(5), 531–543.