Borehole Thermal Energy Storage and its Application to Store Solar Thermal Energy. CFD Analysis

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Abstract

Borehole Thermal Energy Storage (BTES) has become interesting in application to heating, cooling, and air conditioning of commercial and residential buildings. It is combined with heat pump and solar collectors to help in efficiently reducing the electricity demand for heating, cooling, and air conditioning during peak hours. But, the usage of BTES is limited by its low heat transfer rate during charging/discharging regimes. Therefore, performance of BTES needs to be thoroughly studied. One of the ways to better understand the working mode of BTES, numerical analysis needs to be applied. Thus, in the present paper, heat transfer between shallow soil and BTES during charging and discharging periods simulated in two and three dimensional computational domain and results are analyzed. The results show that the temperature of the ground around BTES reduces significantly after several hours of its operation. Therefore, to keep the stable working condition for BTES, it should be assisted by solar collectors.

I. Introduction

According to the recent studies, buildings consume significant portion of worlds' energy resources and it is one of the main contributors to the production of greenhouse gases [1-2] since solid and liquid fuels are burned to heat their interior and provide sanitary hot water to them. Fig.1 illustrates percentage of consumption of worlds' energy resources and the break down of the basics on energy use in buildings [3]. It can be noticed from the break down that heating, cooling and water heating takes the most percentage of energy use in both residential and commercial buildings. In the future, the percentage of consumption of energy resources by buildings will increase as long as more and more buildings are being built in developed and developing countries every year [4]. Therefore, the energy efficiency of buildings is an important issue for future world sustainability. And, to overcome such problems, renewable energy sources should be used to buildings, instead of solid and liquid fuels [5].

There are many renewable energy sources that are suitable for application to buildings. Although, the sun is the simplest and abundant renewable energy source that is appropriate especially for space heating and cooling of buildings, and also for providing domestic and industrial hot water [6]. But, solar energy is not always available when it is needed, that is, at night, during cloudy days and in winter, the solar energy can’t be harvested enough for applications which might be a problematic in terms of its direct usage to space heating/cooling and for domestic and industrial hot water. Therefore, the solar energy must be stored for later use or anytime application [5, 7].

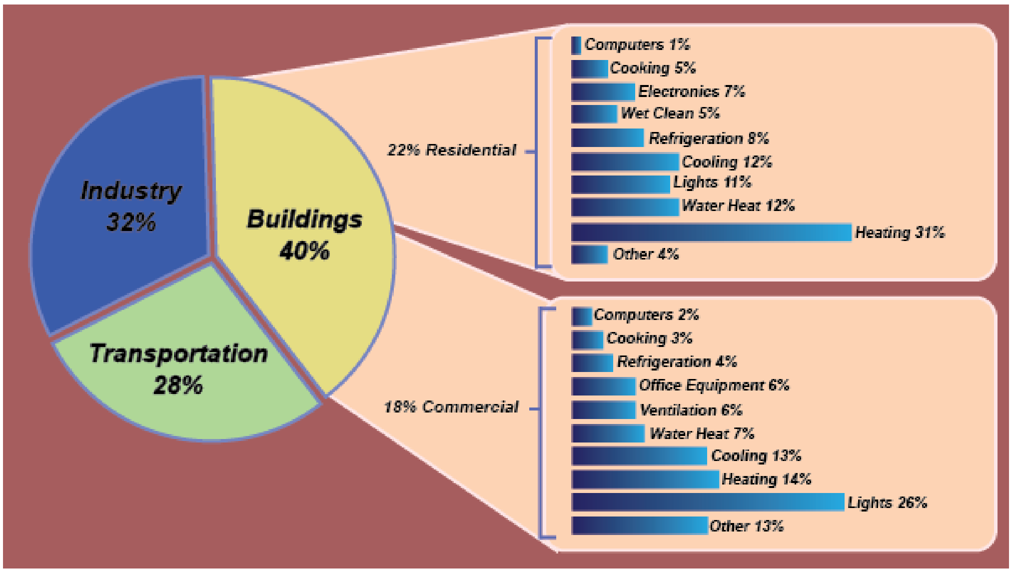

Fig.1 Break down of the basics on energy use in buildings

In the last decades, there are many technologies are being studied to accumulate the solar energy [8]. One of them is borehole thermal energy storage (BTES) where heat and/or cold are stored in the underground by means of borehole heat exchanger (BHE). Such storage consists of one or number of vertically placed to the soil U-shaped plastic tubes. The figure 2 shows one of the examples of such tubes [9]. After drilling a borehole, U-shaped pipe is installed in which the heat transferring fluid flows to transfer thermal energy to/from the ground. Then, the borehole is filled with a grout with high thermal conductivity coefficient. Types of grouts usually are cement mortar, 30% bentonite, 60% quartzite - flowable fill (cement+fly ash+sand), concrete (50% quartz sand). Usually, BHE is coupled with heat pumps for domestic heating and cooling. For single-family houses and other small-scale applications the objective is basically to use the natural ground temperature as a heat source during the heating mode and as a recipient of heat during the cooling mode. Change of temperature of the ground around the BHE should be small. Otherwise, the performance of the boreholes get reduced which in turn affects to the performance of the heat pumps [10]. Therefore, long term usage of BTES for either heating or cooling of houses and other small-scale applications is not efficient since ground temperature around the borehole drops down significantly. But, in such applications the efficiency might be increased if solar energy is applied. In other words, harvested solar energy by means of solar collector can be transferred to BHE to rise the temperature of the surrounding ground. Trillat-Berdal et al. [11] proposed the coupling of solar collectors with the BHEs, to improve the natural ground recovery and maintain a stable temperature in the ground around the borehole. In the present paper, the performance of U-tube BHEs is studied in terms of numerical simulations with reference to some typical time-periodic working conditions and to three different BHE pipe installations: a single BHE surrounded by infinite ground with three types of configurations of the BHE pipe such as along the inner wall of the borehole, close together and average.

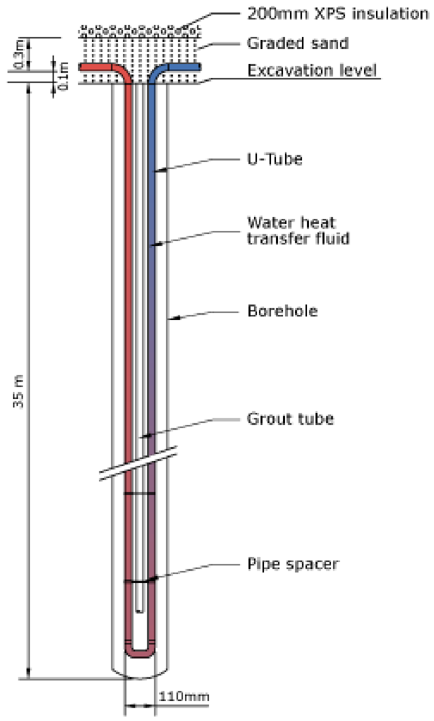

Fig.2 Vertically placed U-shaped plastic tube

II. Methods

2D finite volume simulation is implemented on the bases of Heat Transfer Module of COMSOL Multiphysics. The purpose of using this software is to calculate time dependent thermal performance of the ground near Ground Heat Exchanger (GHE). In other words, temperature change of the soil around the vertical U-tube GHE is analyzed during charge and discharge modes of Borehole Thermal Energy Storage. The calculations are based on two assumptions. First, it is assumed that the diameter of GHE pipe is small comparing with its length. Second, ground temperature is assumed to be constant until certain depth which named as undisturbed ground temperature. In other words, 1-3^0C temperature increase at every 100 meters of depth from the earth surface is not considered. The borehole has a diameter of 110mm, outer diameter d_{out} of the pipe is 33.4mm, and inner diameter d_{in} of the pipe is 29.5mm. The parameters of the soil, pipe and grout is given in table 1.

The performance of GHE is modeled using 2D cross sectional area perpendicular to its length at an average depth. At this cross section, the temperature of the fluid in both inflow and outflow pipes is considered to have stabilized to certain values. The governing heat conduction equation is:

$$\frac{\partial T}{\partial t} + (v \cdot \nabla)v + \nabla(-k\nabla T) = Q \qquad (1)$$

But, we assumed that the heat transfer is steady-state and there is no heat or source term, that is, $Q = 0$. Also, the fluid velocity is not considered since its temperature is given as a boundary condition to the inner wall of the pipe. Thus, the energy equation is the simple heat conduction through different solids. The boundary conditions are same as with operation modes of BHE which is listed in table 2. In the discharging mode, it is considered that the heat transferring fluid is heated by solar collectors or waste heat from buildings. In other words, in order to increase the soil temperature around BHE, the solar energy or waste heat from buildings is used. In the charging mode, the underground generated thermal energy heats the fluid to transfer the energy into heat pump which in turn is used for space heating/cooling.

Parameters	**Value**
Soil	
Thermal conductivity k_{soil}	2.5 W/m K
Specific heat capacity $c_{p,soil}$	840 J/kg K
Density ρ_{soil}	2800 kg/m^3
Grout	
Thermal conductivity k_{gr}	0.81 W/m K
Specific heat capacity $c_{p,gr}$	1600 J/kg K
Density ρ_{gr}	1200 kg/m^3
Polyethilene Pipe	
Thermal conductivity k_{pipe}	0.43 W/m K
Specific heat capacity $c_{p,pipe}$	2300 J/kg K
Density ρ_{pipe}	940 kg/m^3

Table 1. Parameters of materials used in simulation

Modes of operation	
Undisturbed soil temperature T_{soil}	18^{0}C
Fluid outflow temperature in discharging mode $T_{out,d}$	30^{0}C
Fluid inflow temperature in discharging mode $T_{in,d}$	33^{0}C
Fluid outflow temperature in charging mode $T_{out,c}$	17^{0}C
Fluid inflow temperature in charging mode $T_{in,c}$	14^{0}C

Table 2. Temperatures of Borehole Heat Exchanger system and materials

The Fig.3 illustrates one of the examples of the combination of BHE with heat pump and solar collector. As it can be seen from that picture, the solar collector may charge the borehole thermal heat storage and/or it can be used for heat pump.

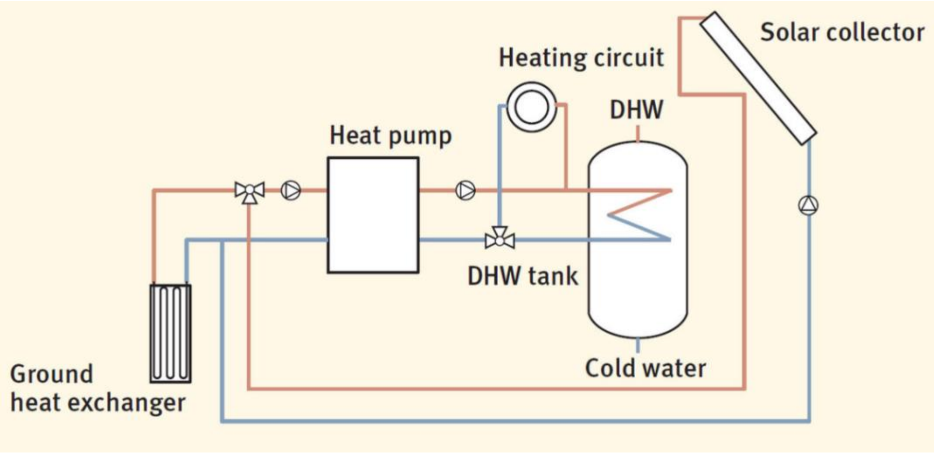

Fig.3 Combination of BHE with heat pump and solar collector

Results and Discussion

Figure 4 is created by computing thermal performance of BHE using equation (1). In this case, the simulation represents the case where the ground temperature is absorbed by heat transferring fluid to transfer the thermal energy to the required place. Here, we assumed that at the beginning of the simulation, temperature of the grout and soil are same which is equal to undisturbed soil temperature 18^{0}C. According to figure 5, temperature of the soil drops by approximately 1^{0}C for every 90 minutes. If we assume that during summer, heat pump works around 20 hours to cool a single family house, and if soil temperature is kept above heat pump temperature efficiency by means of solar collector during daytime, efficiency of BHE is not significantly reduces. But, single BHE is not efficient for larger buildings since such temperature drop (Figure 5) leads to lack of thermal energy for heat pumps. Therefore, an array of BHE must be used to supply required thermal energy to large buildings.

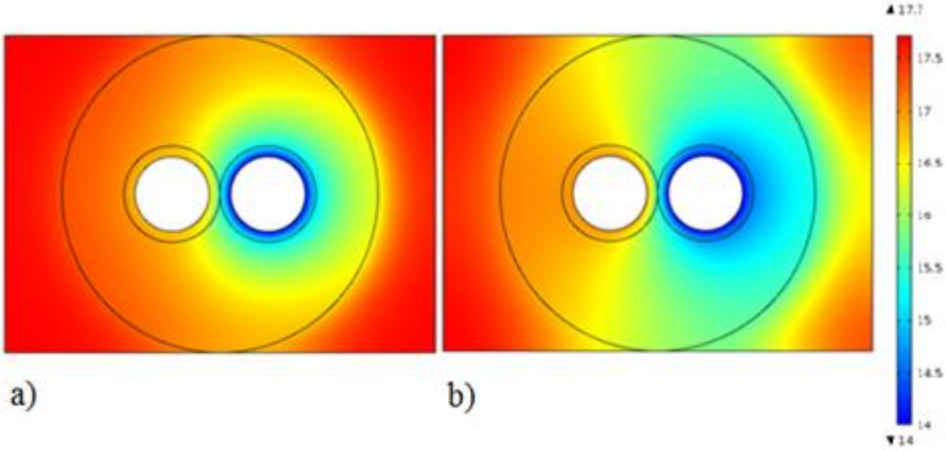

Fig.4 Temperature change around the borehole heat exchange during discharging process for the case of pipe configuration: close together; a) after 30 min; b) after 90 min. The temperature scale is in Celsius.

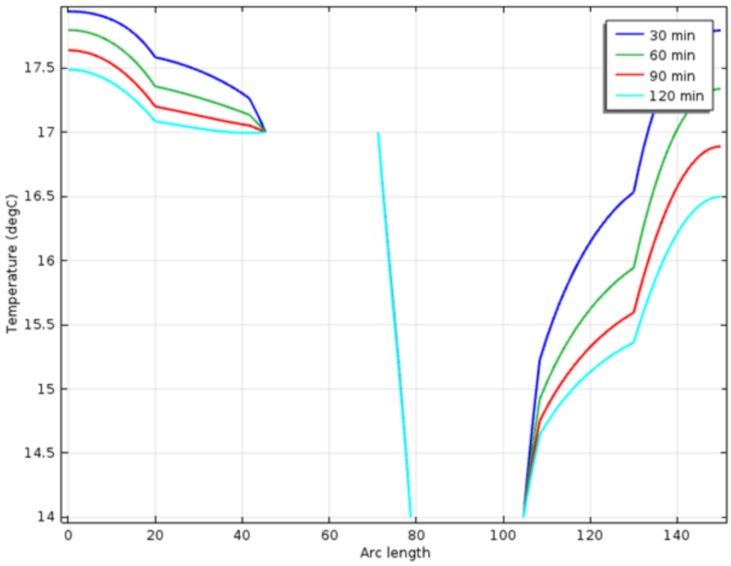

Fig.5 Temperature change around BHE every 30 min until 2 hours. Close together configuration. Arc length represents the line that crosses centers of all circles (that is, borehole circle, pipe circle)

Now, lets consider the cased where pipe configurations are: 1) average; 2) close to outer wall; As, it can be seen from Furgires 6 and 7, making longer distances between pipes, does not allow significant heat stransfer from inflow pipe to outflow pipe in both charging and discharging cases. From Figure 7, it can be notised that temperature drop for every 30 minutes is almost same as close together configuration case, but here temperature change is significant pipe inbetween also. In figures with curves, the arc length denotes the line that crosses the center of all the circles (pipes, borehole) and connects the left and right ends of the simulation domain. According to the CFD results, figure 4 and 6, temperature drop is significant since grout usually has a higher thermal conductivity but it takes some time for heat transfer from the soil to a grout. Therefore, the heat transfering surface between soil and grout needs to be increased for efficient heat transfer.

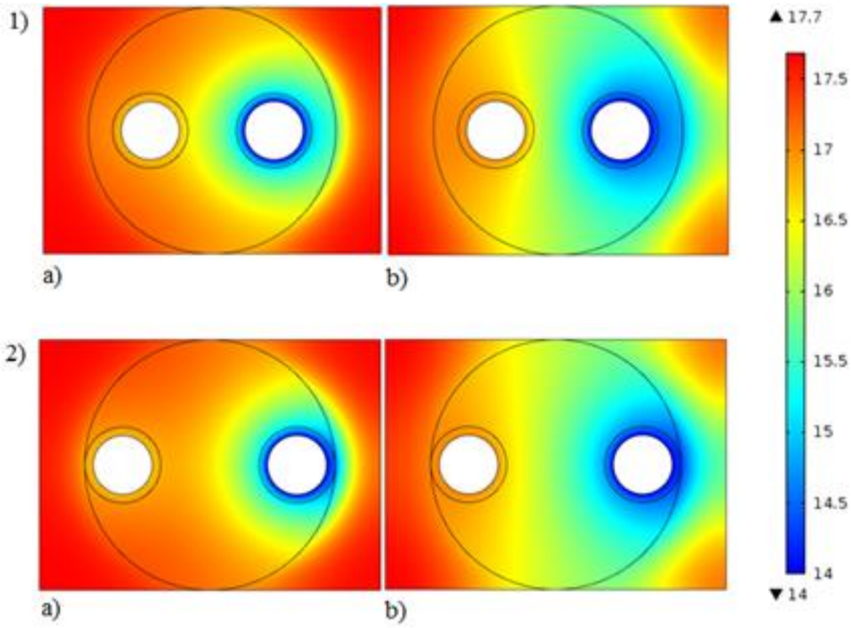

Fig.6 Temperature change around the borehole heat exchange in case of pipe configuration: average and close to outer wall; a) after 30 min; b) after 90 min

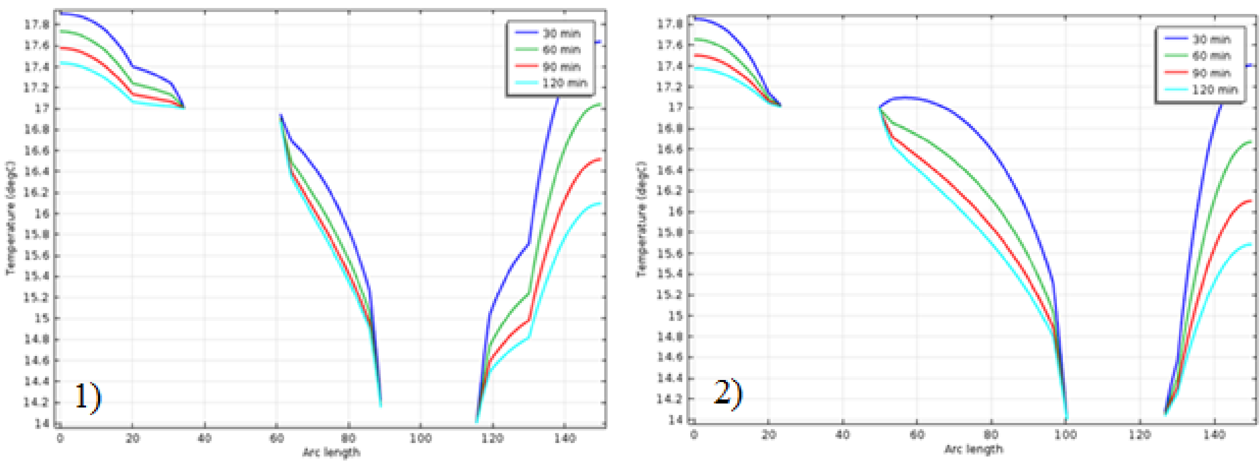

Fig.7 Temperature drop around BHE every 30 min until 2 hours. Pipe configuration: 1) 1) average; 2) Close to outer wall of the borehole

When discharging takes place, the temperature change around the BHE is illustrated in Figure 8 for different pipe configurations. In discharging case, the temperature of inflow is 33^0C and outflow is 30^0C. The Figure 8 shows temperature increase around the borehole at a) 30 minutes and b) at 90 minutes for all pipe configurations. The grout is heated noticeably already after 30 minutes changing its temperature from 18 to about 24 Celsius. And, to rise the temperature of the whole grout in case of close together configuration, it takes about 90 minutes, after that the soil starts gain some thermal energy. But, close to outer wall configuration transfers more thermal energy to surrounding soil than any other cases in a short time which seems more efficient pipe configuration than overs. Thus, in case of short-term application of BTES with single U-tube pipe, solar collector must be used for BHE around 6 hours with that given temperature of heat transferring fluid. If the array of single U-tube BHS applied, the thermal interaction of borehole heat exchangers must be taken into account including thermal resistance of the soil, pipe and grout.

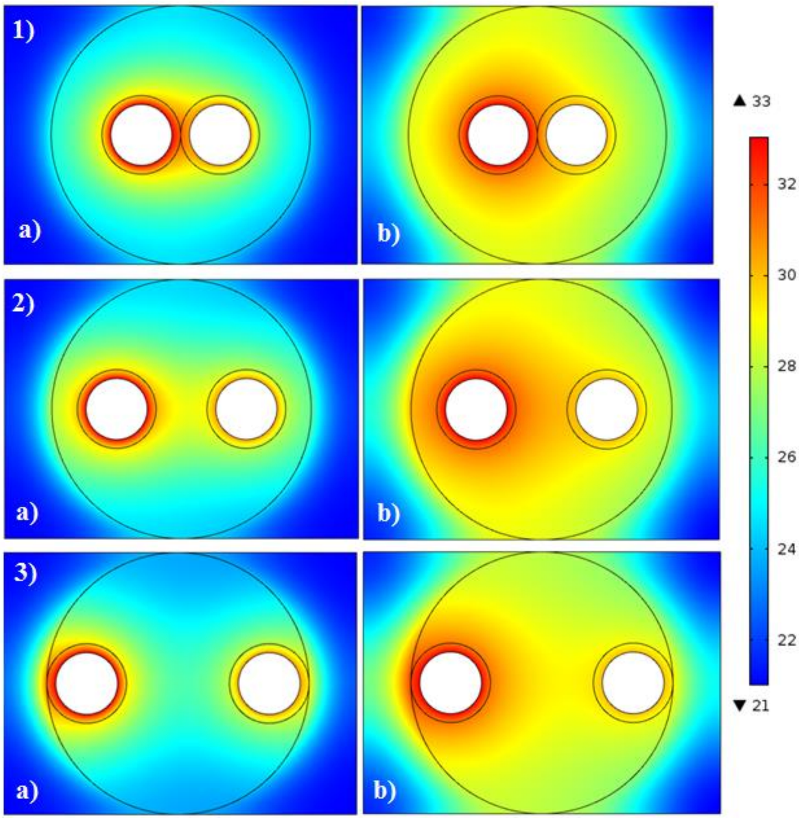

Fig.8 Temperature change around the borehole heat exchange during discharging process for cases of pipe configuration: 1) close together; 2) average; and 3) close to outer wall. Time: a) after 30 min; b) after 90 min

We are mostly interested in how long the temperature change is moved in the soil per minute or per hour. In other words, the thermal energy flux in the soil is very important when the ground is used as heat storage. Of course it depends on composition of a soil where high and low thermal conductivity materials exist. But, this complicated problem can be simplified for computational modeling if we assume the soil does not contain any fluid and also if we do not take into account the porosity of a soil, that is, soil is assumed to be a single component material without porosity and heat is transferred isotropically. Thus, to calculate how much time is needed during thermal energy transfer per meter, let's consider the temperature change around the BHE, that is, figures 5, 7 and 9. According to figure 5, thermal energy flow is at a rate of 18 centimeters per hour, and it rises the temperature of the ground during charging period by one degree. Thus, 10 hours of constant operation of single BHE, changes temperate of surrounding soil with the radius about 1.8 meters. Therefore, if the array of BHE is used for borehole thermal energy storage, distance between two neighboring BHE must be at least 2 meters for short term (day time discharge, and night time use) application purposes of BHE array.

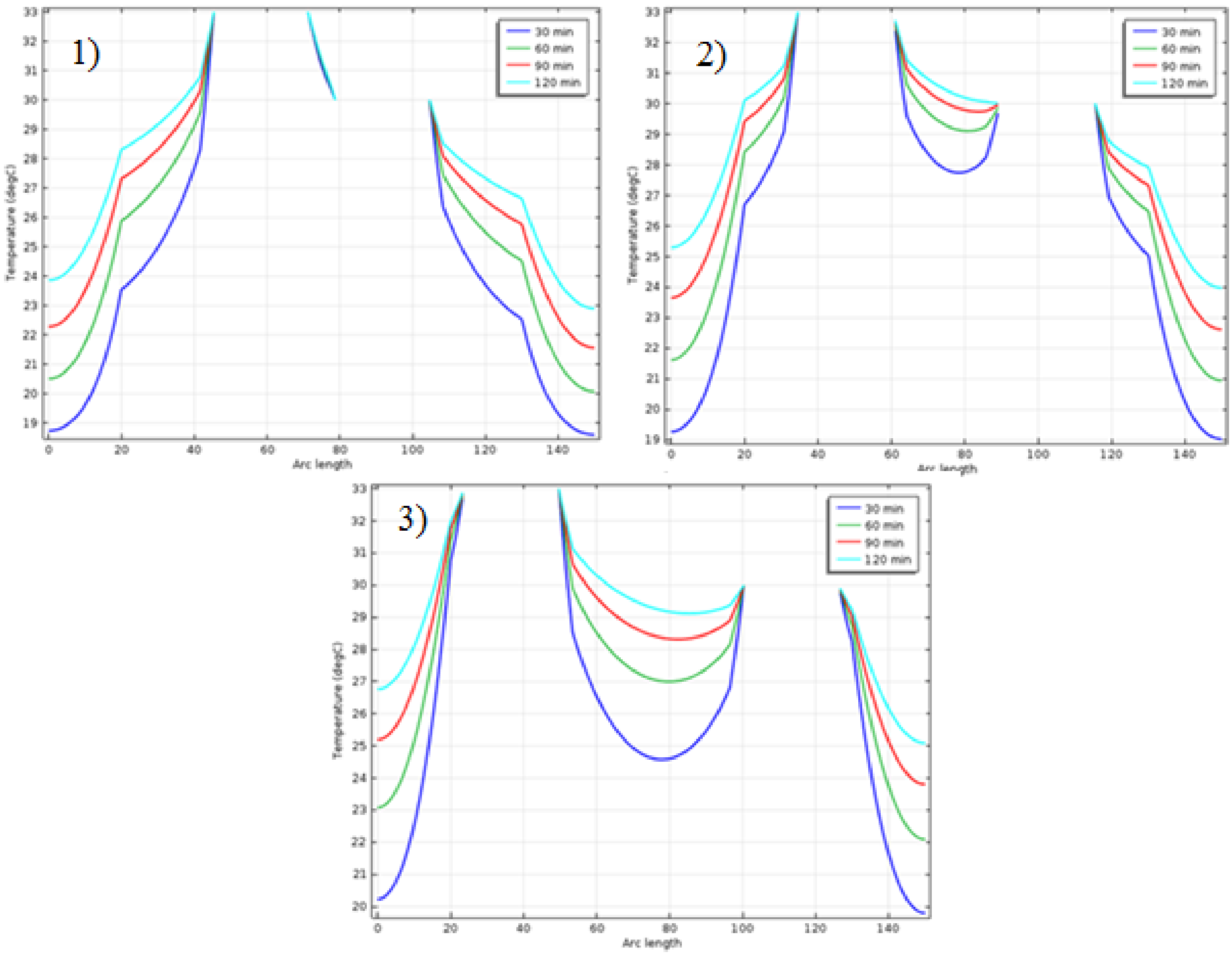

Fig.8 Temperature change around BHE during discharging case. 1) Close together configuration; 2) Average distance pipe configuration; 3) Outer wall pipe configuration.

Three dimensional analyses for evaluation of BHE performance is challenging and yet interesting since it includes fluid flow inside pipe, heat transfer between fluid and soil. And, results of numerical simulation gives better understanding of heat and mass transfer inside and outside of the borehole heat exchanger.

The authors of the paper developed a 3 D modeling of working mode of BHE and the figure 9, a) shows the computational domain and geometry of the domain. In this case, only one of the pipe configurations is considered, and it is average configuration. And, borehole diameter, inner and outer diameters of the pipe are same as for 2 D case, and the grout is concrete in this case. The length of the pipe is 20 meters and the fluid is water which flows with the velocity of 0.1 m/s. Figure 8 b) and c) shows the temperature drop around the BHE during charging case after 1 hour. The soil temperature was initially at 18^0C and the fluid temperature is 14^0C when entering the pipe. The fluid flow in the pipe is assumed to be laminar. In the future this model will be developed further which will include more realistic physical phenomena that occurs during charging and discharging of U-shaped vertical borehole heat exchanger.

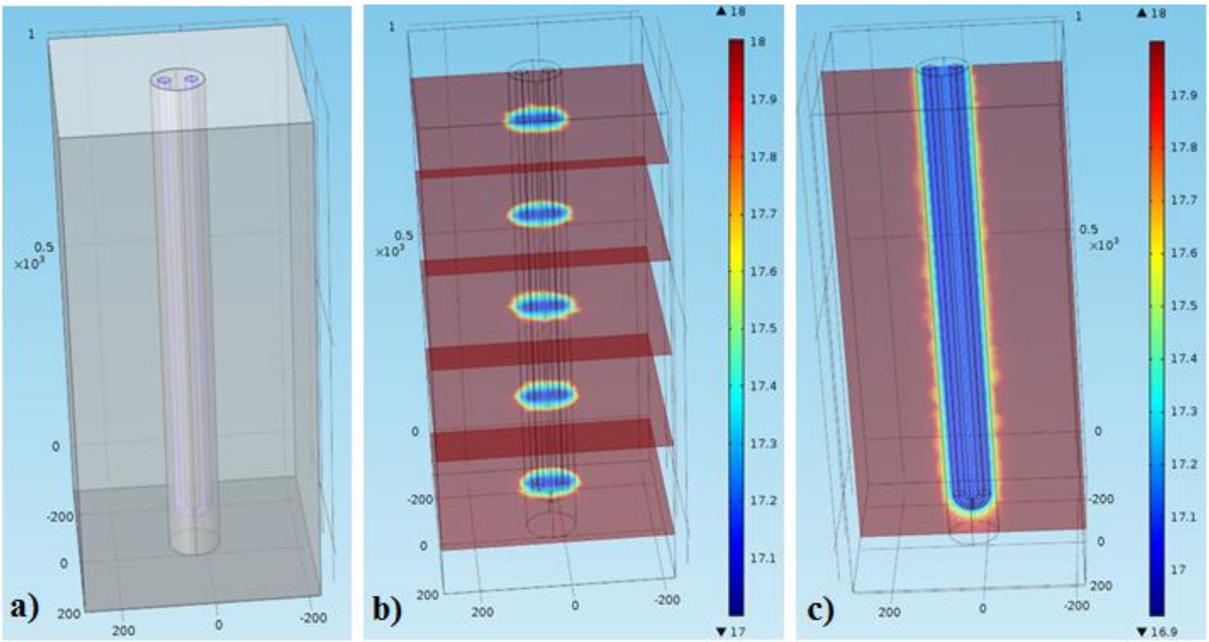

Fig.8 Computational domain and temperature distribution in the form of several horizontal slices b), and vertical slice c), around u-shaped vertical borehole heat exchanger

Conclusion

Borehole thermal energy storage has perspective in storing solar thermal energy for later use but its performance depends on several parameters such as ground or soil type, depth of the exchanger, type of grout and pipe configuration. Successful establishment of the borehole heat exchanger (BHE) assists in using the stored solar energy in the underground to apply for heating and cooling of buildings. But in order to understand the working mode of the BHE, numerical simulation should be used.

Two dimensional modeling of performance of BHE is studied in the current paper and temperature changer around BHE during charging and discharging cases is simulated. And, it was found that 10 hour operation of the BHE changes the temperature of the soil which reaches the distance with radius 1.8 meter around BHE. Moreover, three types of pipe arrangement is studied, namely, close together, average and along the wall. And, the heat transfer processes around these pipe arrangements are investigated. It was found that the close together case is not optimal since between inflow and outflow thermal energy is transferred. Therefore, the average distance pipe configuration seems the most appropriate.

Three dimensional numerical analysis of the working regime of the borehole heat exchanger is investigated and results are demonstrated in terms of simulation results. In this case, the flow in the pipe is taken to be laminar for making the problem less computationally expensive. But, in the future the three dimensional model will be developed to include all the fluid mechanics and heat and mass transfer processes during charging and discharging regimes of borehole heat exchanger.

According to the results it can be noticed that the borehole heat exchanger is limited by low conductivity and low heat transfer, therefore, it is not able to cover the energy demand during peak loading period for heating and cooling of buildings. Thus, it is better to combine the borehole thermal energy storage system with other systems. One of the promising heat storages is latent heat storage but it is better applicable for short term storage. Meanwhile the BTES can be used for long term heat storage, and if these two storages are combined it is possible to satisfy the thermal energy demand for heating, ventilation and air conditioning systems for daily and longer periods.

6. REFERENCES

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