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Optimizing the Distance between Boreholes with Helical Shaped Ground Heat Exchanger

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ABSTRACT

Energy use in buildings represents a major share of the overall energy used in developed countries. Ground source heat pump (GSHP) systems are becoming widespread due to their high energy efficiency both in heating and cooling mode. The installation cost and performance of GSHP systems can be greatly affected by optimal design of ground heat exchangers (GHEs). Two parameters affecting the helical shaped GHE's performance are GHE spacing and helical configuration of the pipe. In large scale GSHP applications, more than one GHE is needed, therefore determining the distance between GHEs becomes as an important issue. In this work, the effects of distance between helical shaped GHEs on the heat transfer ratio (HTR) are studied. Performance of GHE is determined and optimal distance is examined. Furthermore, the influence of the pitch between the turns of the helix on HTR is numerically studied in COMSOL environment. The available experimental data are used to validate the numerical results. It is seen that they are in a good agreement. Computational model in this study may provide useful guidance for designing the helical shaped GHE for GSHP systems.

1. INTRODUCTION

In the recent decades, energy consumption for building sector has increased in multifold around the world. Efforts are being made to develop alternate energy sources for meeting the demand of building heating and cooling loads. One of the best alternate ways is the use of ground source energy, which is green and sustainable.

This energy can be utilized using ground source heat pump (GSHP) system, which is well established in Western and European countries for space heating applications.

At deeper layers, the ground temperature remains almost constant throughout the year and is usually higher than that of the ambient air during the cold months of the year and lower during the warm months (Omer, 2008 and Ochsner, 2007). GSHP systems use some electricity to extract heat from the ground and deliver to the space to be heated, thus they indirectly contribute less greenhouse gas generation than the conventional heating systems.

In many developing countries, in the absence of GSHP, conventional electric resistance heaters are used for space heating in winter and air conditioners for space cooling in summer. With increase in average temperature of earth due to global warming, the need for space cooling systems in summer season is augmented, resulting in significant consumption of centrally generated electricity.

Hence there is an urgent need to find alternative systems for the present air conditioners and heaters. Ground Source Heat Pump (GSHP) will be a viable solution as it can be used for both heating and cooling purpose with lesser electricity consumption and with an indirect benefit of reduction in greenhouse gas emissions.

In general when a GSHP system is designed to operate for heating mode, it will produce higher COP during heating operation (Ozgener,Hepbalsi, 2004).

In order to save electricity input to the GSHP system operating both in heating and cooling modes, the system parameters have to be optimized to achieve a higher COP. The influencing parameters

of GSHP on the COP can be classified into four groups (Fig. 1) (Sivasakthivel,2014): ground heat exchanger parameters, heat pump parameters, ground parameters and climate and distribution parameters. Optimizing these parameters to get high performance is an important aspect in the performance analysis of GSHP systems. With regard to optimization of ground heat exchanger parameters, few research works have been published (Rabin, Korin,1996 and Congedo, Colangelo, 2012).

Rabin and Korin made a similar contribution. They modelled the helical pipe with a series of horizontal rings with a constant pitch between them and they solved this model by means of the finite difference method; they also compared the results with experimental data obtained from field test.

Li and Lai proposed an analytical approach to solve the heat conduction problem in infinite and semi-infinite anisotropic media with a helical line source, which was created by integrating a point source along the helix. In that study, they did not use the thermal capacitance of grout. Heat transfer at ground level was not analyzed.

A detailed literature survey on GSHP research indicates that only very few research works have been reported on the study of helically shaped GHE's spacing and the pitch between helixes.

The present study focuses on the application of a GSHP system with vertical helical shape heat exchangers to exploit the thermal interaction between a heat pump and the ground. The thermal performance of GSHP system depends heavily on the heat transfer between heat exchangers and its surrounding soil/rock. To ensure high efficiency of GSHP systems, thermal efficiency of the GHE becomes as an important issue. In large GSHP applications, more than one heat exchanger is needed. Therefore success of GSHP applications strictly depends on good design in the ground side. Optimizing the design and performance of GSHP system requires accurate knowledge about GHE spacing.

Nomenclature

k_{PE}	Thermal conductivity of PE tube	L_p	Pitch between helix turns
C_{PE}	Specific heat capacity of PE tube	D	GHE diameter
ρ_{PE}	Density of PE tube	d	Distance between borehole
k_{eff}	Thermal conductivity of ground	n	Number of turns
C_p	Specific heat capacity of ground	N	Number of GHE
ρ	Density of ground	L_{GHE}	GHE vertical length
r_i	Internal radius of PE tube	T_{avg}	Inlet and outlet average water temperature
r_o	External radius of PE tube	T_e	Undisturbed ground temperature
q_{sGHE}	HTR of single GHE	q_{cGHE}	HTR of critical(central) GHE
$T_{avg\text{-}i}$	Average temperature of inlet water	$T_{avg\text{-}o}$	Average temperature of outlet water

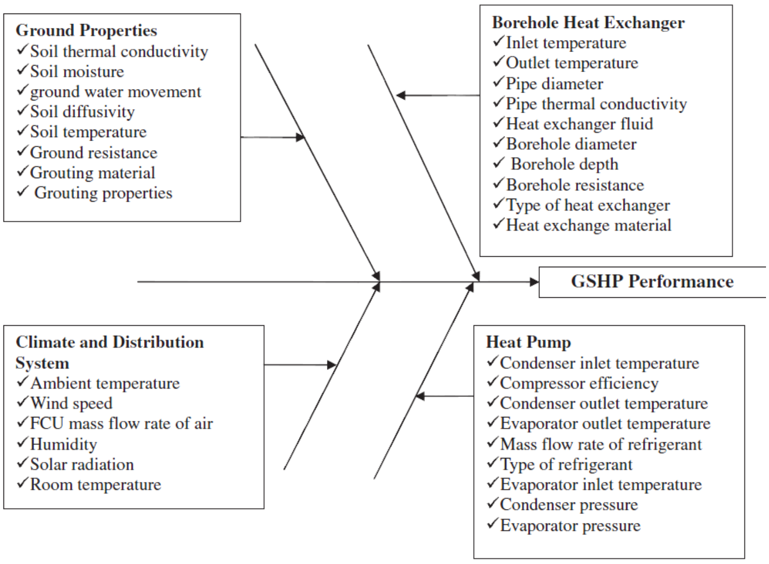


Figure 1: Cause and effect diagram for GSHP system.

In the present paper, thermal interaction between helical shaped GHEs for four different configurations is examined. Averaged unit HTR value of the most critical borehole in each configuration is compared with that of single borehole to determine the performance loss for 3 months non-stop operation. Variations of performance loss of the critical boreholes due to thermal interactions of neighbor heat exchangers with both time and distance are analyzed. The calculations for 3 months non-stop operation, which are the possible worst cases, are carried out. During these investigations, the temperature distributions around the critical heat exchanger are examined. Furthermore, pitch magnitude effects of the helix on HTR is conveyed for single GHE and the results are compared with available experimental data.

2. MODEL DESCRIPTION

In this study, computer modeling of 1, 2, 3 and 5 helical-shaped GHEs are described. Performance losses due to thermal interactions for different GHE spacing, in 3 latter cases are determined. Distances between GHEs vary from 1 m to 11 m. Characteristics of different parameter that were used in this modeling are shown in the table 1 and table 2.

Following assumptions were made in all modeling:

- Soil is isotropic and homogeneous and also contains some water in some layer of it. Therefore because of these water amounts in some layer of the soil thermal conductivity assumed higher than the average thermal conductivity of the soil.

- The temperature distribution along the vertical direction has a negligible influence.

- The fluid temperature in the GHEs is determined as average of inlet and outlet temperature.

Table1

Characteristics of the helical-shape GHE

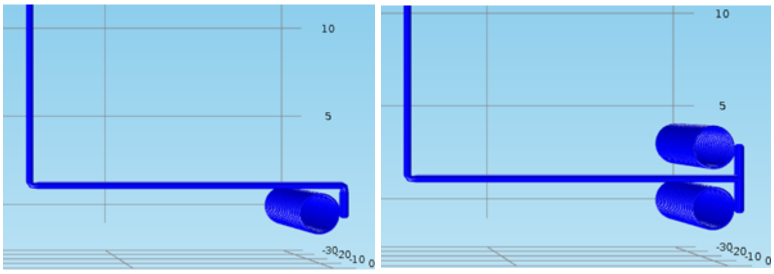
r_i [mm]	10.5
r_o[mm]	12.5
L[mm]	80
D[mm]	400
n	36
L_{GHE}[mm]	3000
K_{PE}[W $m^{-1}K^{-1}$]	0.38
C_{PE}[$Jkg^{-1}K^{-1}$]	1900
ρ_{PE} [kg m^{-3}]	958

Table2 Characteristics of ground and working conditions

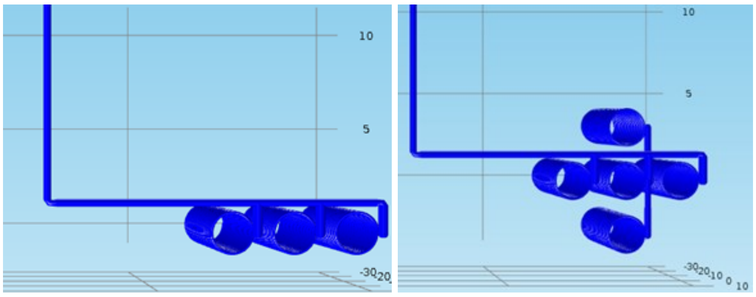
k_{eff} [W $m^{-1}K^{-1}$]	3.5
C_p [j $Kg^{-1}K^{-1}$]	850
ρ [Kg m^{-1}]	2160
T_{avg} [^oC]	39.6
T_e [^oC]	18.5
T_{avg-i}[^oC]	40.01
T_{avg-o}[^oC]	39.17

2.1 Single, two, three and five Helical Shaped GHE Model

The vertical helical-shape GHE is simulated by using the COMSOL software. It contains two domains: ground and polyethylene pipes. In order to find the optimum distances between helical-shape GHEs in vast areas we need to determine the performance losses for critical GHE. To do so, we design 2, 3 and 5 GHE, shown in Fig2 which the distance between them is d. By determining the performance loss versus different d s, the optimum distance between GHEs can be found.



(a) single GHE (b) two GHEs



(c) three GHEs (d) five GHEs

Figure 2: Different configuration of GHEs

3. RESULTS AND CONCLUSIONS

In this part the results are divided into the three parts:

3.1 Single helical shaped GHE computational results and its validation

3.1.1 Model Validation

The accuracy of the simulation approach is verified by comparing the simulation and experimental results of a test run. Here, only one GHE is used. The inlet temperature and the flow rate of the experiment are taken as transient input values of the model. It is noteworthy that the average inlet fluid temperature is 38.8 ^{o}C and the flow rate is 15.9 Lit/min. Experimental results are obtained for 120 hours non-stop operation and the results of computational model are based on aforementioned assumptions. It is noteworthy this study is just considered the cooling mode because the test results are obtained from experimental setup which work in cooling mode. The test results are obtained in cooling mode and our simulation is also for cooling mode.

As it is shown in fig 3 experimental and computational results are in a very good agreement and it shows the accuracy of our modeling.

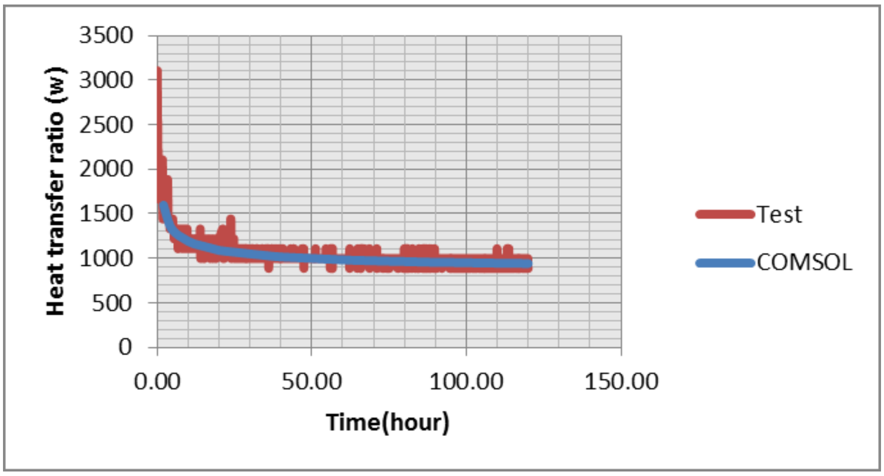


Figure 3: model validation for 120hours non-stop operation experiment

3.2 Two, three and five helical shaped GHE computational results and performance loss in each GHE

3.2.1 performance losses

Based on the single GHE outcome, the same work is applied for 2, 3 and 5 GHEs. The amount of HTR in critical GHE is determined computationally and performance losses due to the single GHE operation are calculated.

Fig 4 indicates the performance loss in different configurations of GHEs. Based on designer's objective, optimum distances between GHEs can vary. Thus, analysis on performance and costs of different configurations has been a task for scholars and engineers to study.

In engineering problems the performance losses less than 5% is usually acceptable. As it was shown in fig 4 the performance losses is less than 5% in d more than 5m for two GHEs, more than 7m for three GHEs and more than 9m for five GHEs.

Performance losses can be found by the following expression:

$$\text{Performance loss} = \frac{\text{HTR of single GHE - HTR of critical GHE in more than one GHE}}{\text{HTR of single GHE}} = 1 - \frac{q_{sGHE}}{q_{cGHE}}$$

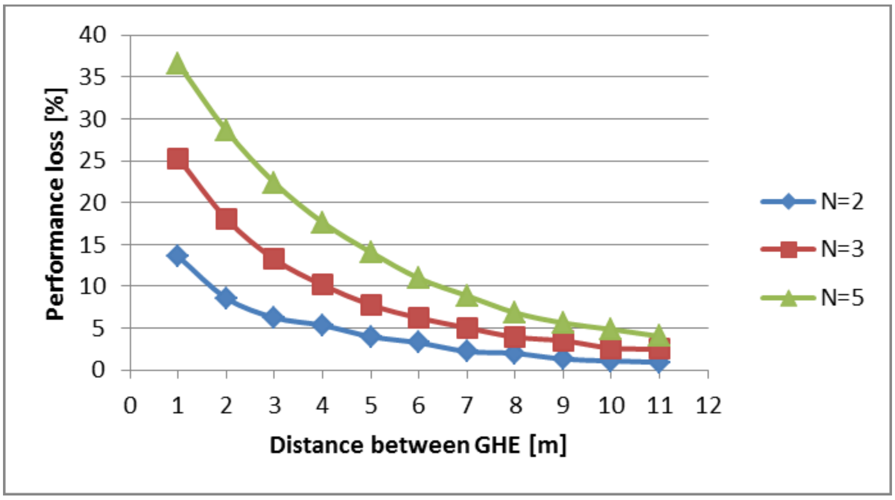
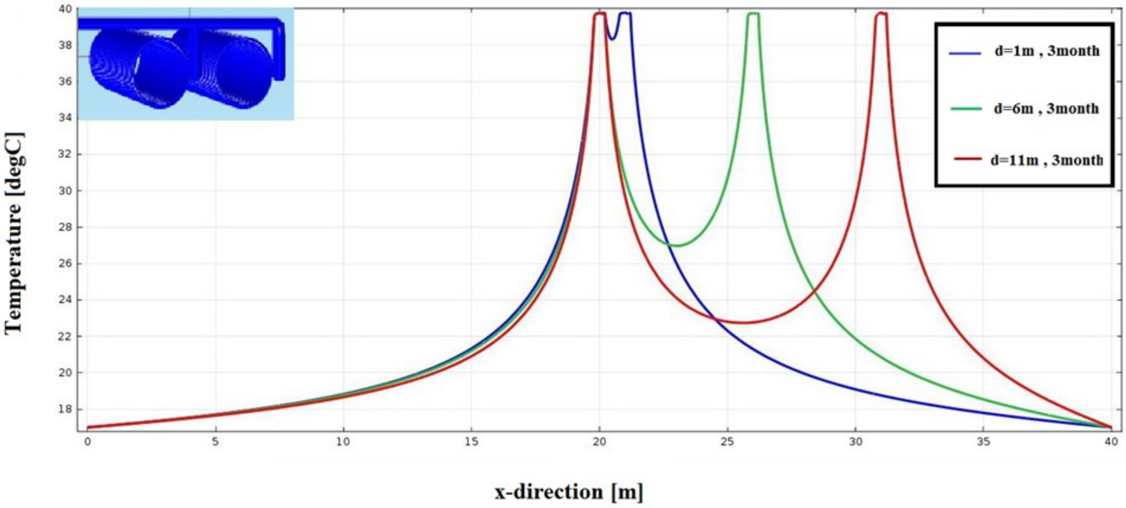


Figure 4: Performance losses of critical GHE at the end of 3months non-stop operation

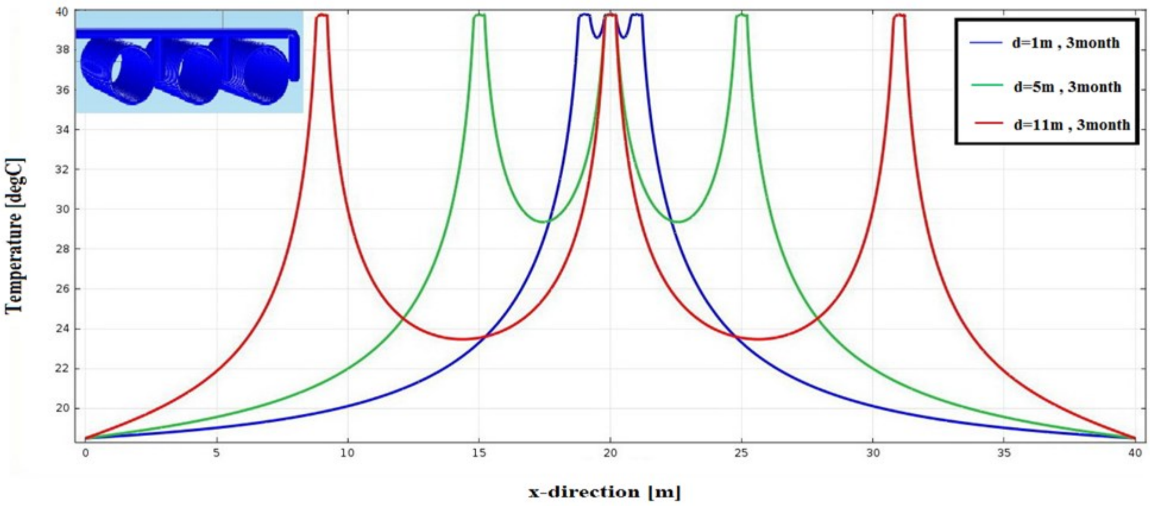
3.2.2 Temperature distribution in the ground

Fig 5 shows the ground temperature profiles at various distances from the GHE after 3months.The temperature profiles in the ground are affected by GHEs configuration.

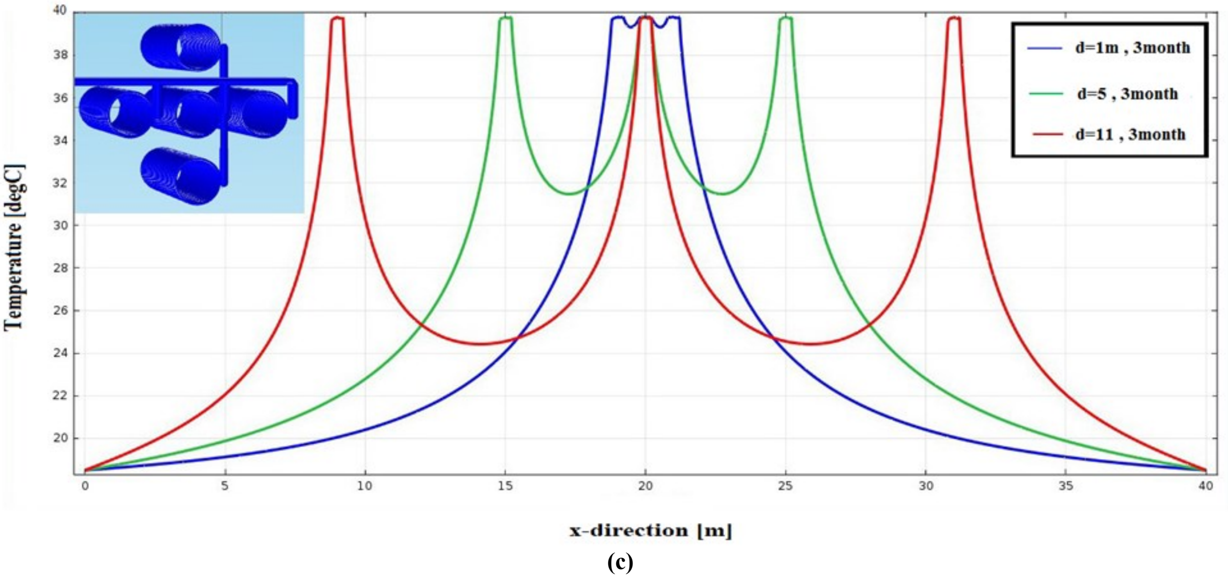
Figure 6 shows the temperature distribution in the ground at the end of 1,2,3 months. It is obvious from these figures that the ground temperature is raised by the time. It can also be noticed that the temperature response at any location keeps rising, and does not approach any steady state as time elapses.



(a)

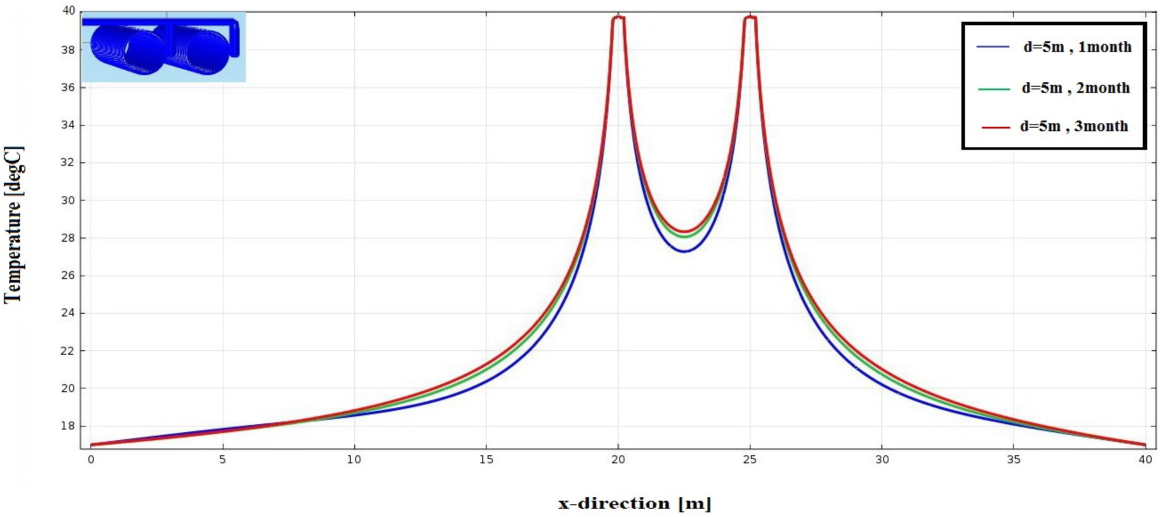


(b)

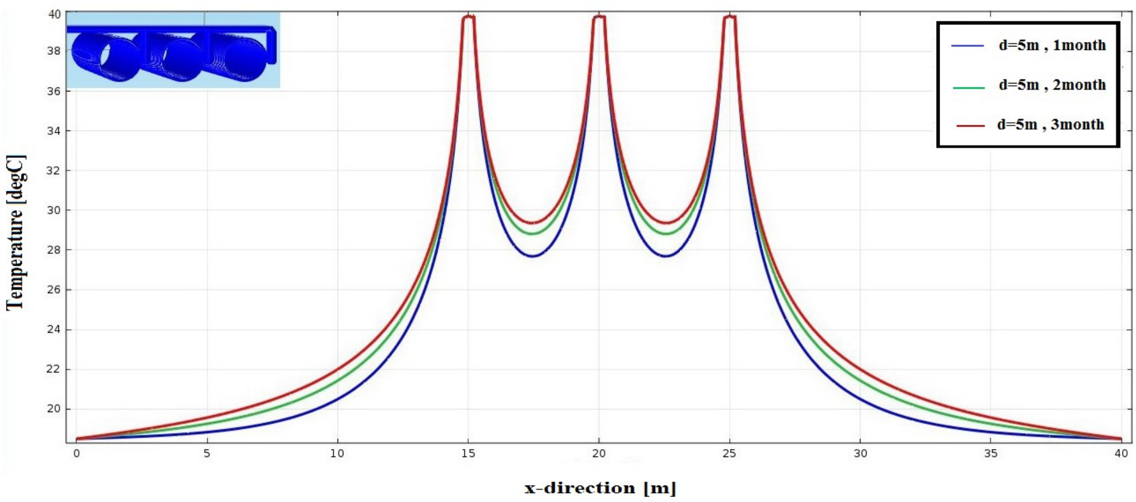


(c)

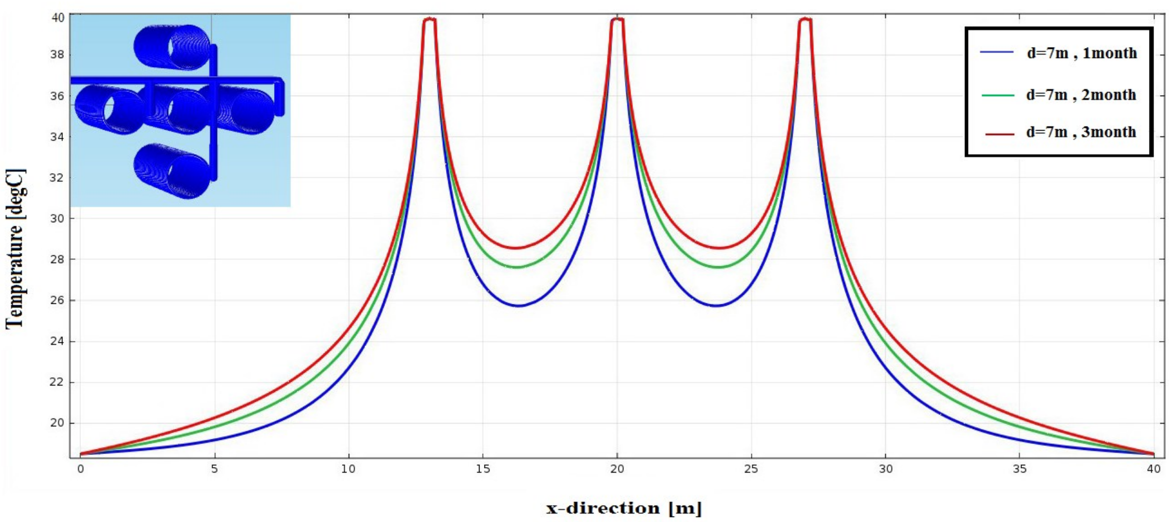
Figure 5 (a),(b),(c): Effect of distances between GHEs in temperature distribution at z=1.5m and at the end of 3months non-stop operation



N=2, d=5m



(b) N=3, d=5m



(c) N=5, d=7m

Figure 6 (a),(b),(c): Temperature distribution in the ground at the end of 1, 2, 3 months non-stop operation

3.3 The influence of the pitch between the turns of the helix on HTR

The pitch between the turns of the helix is one of the geometric parameters that directly affect the HTR and initial cost of the installation for the system. This property directly relates to the vertical lengths required to construct the heat exchanger as well as amount of excavation. The same simulations as in single GHE are carried out. At the same time, the effect of pitch between the turns of the helix on GHE performance is considered (Fig7). It is visible that by increasing the L_p, HTR of a GHE is accumulated. Although the performance of the GHE is improved, the total cost of the placing the GHE will become higher and higher by increasing the L_p. Therefore it is important for designers and factories that they know the exact requirements of consumers.

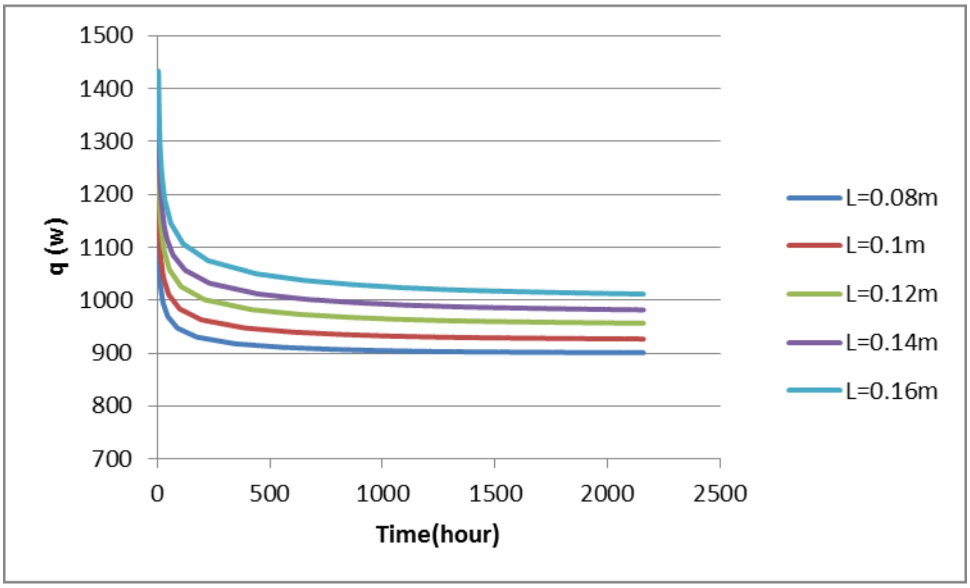


Figure7: Effect of pitch (L_p) on HTR for three months non-stop operation

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