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Analysis of ground heat exchanger for a ground source heat pump: A study of an existing system to find optimal borehole length to enhance the coefficient of performance

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Abstract: - Ground Source Heat Hump is one of the emerging technic to utilize the reservoir of geothermal energy in Europe. The crucial factor is to find the optimal length of the borehole to successfully design a heating system. The length of the borehole varies depending on the geographical area, the capacity of the heat pump and heat load of the desired building in consideration. Several methods have been theorized and validated using the experimental measurements to find the optimal length of the borehole. The most commonly used methods are American Society of Heating, Refrigeration and Air-conditioning Engineers and International Ground Source Heat Pump Association for sizing borehole heat exchanger. In this paper, an existing system is analyzed, for a 60 kilo Watts heat pump in an area of Finland with a ground source 250 meters of Borehole Heat Exchanger. Coefficient of Performance for current scenario is calculated, an optimal length is found for the heat capacity of the heat pump to enhance the performance of the system. Improved coefficient of performance is presented along with an easy method of finding the optimal length of the ground source.

Key-Words: - Borehole heat exchanger, Borehole sizing, Ground source heat pump, Coefficient of performance, Thermal response of boreholes.

1 Introduction

Ground Source Heat Pump (GSHP) is one of the important innovation towards clean energy production. The renewable heat energy production may have been three quarters of the total capacity of a heat pump at maximum efficiency. Research in this area is focused on achieving the maximum efficiency even in a harsh climate (such as Finland) when the heat demand is evidently higher than rest of the year. An optimal Ground Source Heat Pump (GSHP) is cost effective and have high efficiency to produce renewable energy. A ground source is required, which may either be a horizontal or vertical borehole depending on the availability of the area. A heat exchanger pipe is installed in the ground, in which a carrier fluid is circulated, heat transfer takes place from the borehole to the fluid, which enters the heat pump to be distributed to the desired building. Conventional logic dictates that the warmer the carrier fluid enters the heat pump, the less electrical power the heat pump consumes to produce the amount of heat required for distribution. The analysis of sizing borehole and configuration may be divided into two categories; first would concerned the thermal response of the borehole when supplied with the ground load. Second relates to the Coefficient of Performance (COP) of the heat pump with respect to time. Contemplating the effectiveness of the Ground Heat Exchanger (GHE) may necessitate conducting a Thermal Response Test (TRT) which led to the finding of the ground thermal conductivity and thermal resistance of the ground participating typically 15% to 25 % of the total resistance at design condition (Kavanaugh, 2010). TRT is being conducted all over Finland since the demand of GSHP increased in the recent years (Kallio et al., 2011) using the distributed sensing method to calculate the thermal response of multiple layers in a borehole (Hakala et al., 2014). Typical GHE may be installed using U-tube or Coaxial tube depending on the availability and the cost. The performance of both has been realized to be little difference (Acuna, 2013). Another component effecting the length of GHE is thermal resistance. Lamarche et al., (2010) evaluates 2D borehole thermal resistance for GSHP system. Conformal-mapping method has developed to predict the thermal properties of the U-tube heat exchanger (Liang et al., 2014). Raymond et al., (2011) presented a numerical evolution method to find the Thermal resistance of the grout and borehole and validated with the help of simulation, borehole temperature rise is presented during the short time steps and compared with at least five methods. Sharqawy et al., (2009) improved on the effective pip-to-pipe thermal resistance in a borehole borrowing from Eskilson (1987) depicting a numerical solution, validation of this method is done by comparison with three other methods. Short circuiting effect on the TRT is stated and analysed using RMSE values taken from Hellström (1991), factors effecting the short circuiting is explained by finite element modelling (Li et al., 2014). A novel approach to conduct a TRT is developed with a low power source of just 1 kW validated with Comsol framework with the conventional analogy of current flowing in the circuit (Raymond and Lamarche, 2014). Bondos et al., (2011) improved parameter estimation keeping the air temperature variation into consideration with a variable heat rate. Analysis of ground-water influenced borehole is presented using the conventional line source method and moving line source using 2 U-tube heat exchanger pipes, compared with a commercial software EED and correction factor is introduced to this method (Wagner et al., 2013). Classical interpretation of the thermal properties of the ground is conducted to perform further analysis of the ground. Next step may include finding the size of the GHE in order to provide the optimal response. If the size is of GHE is larger than necessary, it will result into over estimation of the capital. On the other hand, if the size of GHE is smaller, it will result into a higher consumption of the electrical power rather than producing renewable energy of the heat pump (Bernier, 2015). Borehole length is crucial when installing a GSHP. Size of a borehole required detail analysis considering the heat pump capacity and heat demand of a building round the year. Heat consumption during winter is evidentially highest than the rest of the year. Kavanaugh and Rafferty, (1997) presented a detailed manual for designing a heat pump. Calculations are performed during the design month of the heat pump installation. A comprehensive analysis is done by Bernier, (2006) to find the length of borehole heat exchanger involving three pulses of effective thermal resistance for 20 years, one month and six hours plus an average yearly ground, the highest monthly ground load and the peak hourly ground load. Ruan and Horton, (2010) stated the IGSHP single borehole method using the conventional line source model. Philippe and Bernier, (2010) provided with spread sheet, a sizing method for single or multiple boreholes restricted from 0.05 m to 0.1 m of the borehole radius.

This paper presents a comprehensive analysis of using a 60 kW heat pump in practice, the size of GHE to perform the operation of the heat exchanger at a maximum efficiency with calculation of COP and realize the thermal response of the borehole using some state of arts numerical method practice in Comsol and compare with the conventional analytical methods for heat transfer in the ground. This paper is part of an ongoing project in the University of Vaasa, Finland in which a heat pump is being used with a 250 m borehole heat exchanger. This analysis will be used to predict the correct size of the GHE and presents the COP of the boreholes when applied with a load. This study is sub-divided in such a way that, first, the efficiency of the heat pump is presented with the existing system, next, the calculation of the optimal length of GHE is performed, and then, thermal response of the optimal result is simulated and presented with the improved COP.

2 Analysis of the existing system

Analysis of the performance of GSHP is related to the ground temperature and the temperature difference between the incoming and outgoing fluid temperature. The desired COP of a heat pump is 4, which means the renewable energy production is ¾ and ¼ is consumed by the heat pump. But in practice, it's more likely varying with the passage of time. The air temperature influence greatly to the ground temperature affecting the inlet and outlet fluid temperature of the heat pump, entering water to the heat pump and leaving water from the heat pump are usually assumed to find the correct length of the borehole. For example, in winter, the air temperature is evidently below zero in Finland on average, which necessitates the use of a carrier fluid which has a low freezing point. For this very reason, a simulation is made to calculate the fluid temperature with the worst case scenario. Comsol is used to build this simulation to find the COP, the algorithm used in this simulation is stated as follows:

- Yearly temperature profile should be known (either hourly or average monthly)

- Geothermal gradient and the initial temperature of borehole should be known
- Heat demand of a building or heat capacity of the heat pump should be provided
- Material property of borehole, ground and carrier fluid should be known (TRT provide material property of borehole)
- Apply initial value and the surface temperature
- Pipe properties should be known or the most common assumption may be made
- Run simulation for the worst case (4 months in the Finnish winter time, in this case)
- Calculate the average fluid temperature at the inlet and outlet
- Find the COP of the heat pump

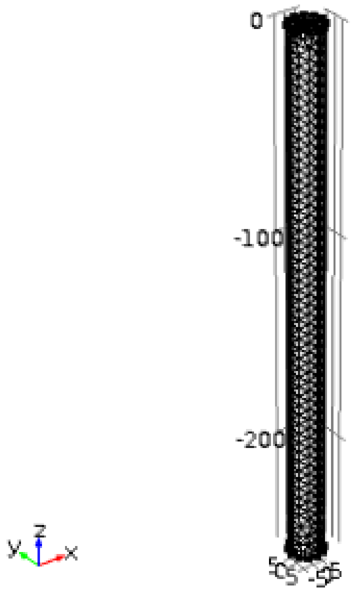

Fig. 1. Geometry of the borehole heat exchanger.

Simulation is implemented by considering a single borehole depicted in Fig. 1 with ground water inside it. Pipe is considered to be polyethylene. The parameters used in the simulation are presented in Table 1. Carrier fluid is assumed to be water (worst case scenario). Average air temperature of Finland (Kemna, 2014) is represented in Fig. 2 in which the lowest average monthly air temperature is -4.7 0C. Initial temperature of the borehole is calculated using the geothermal gradient plus the ground temperature. Borehole initial temperature is depicted in Fig. 3.

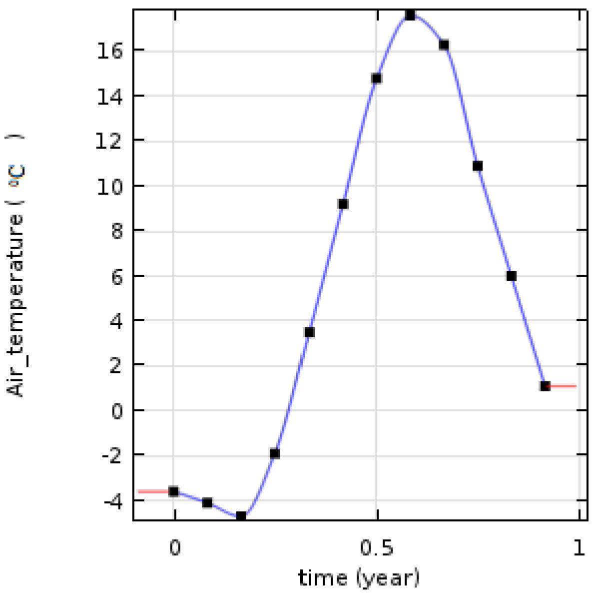

Fig. 2. Average air temperature in Finland.

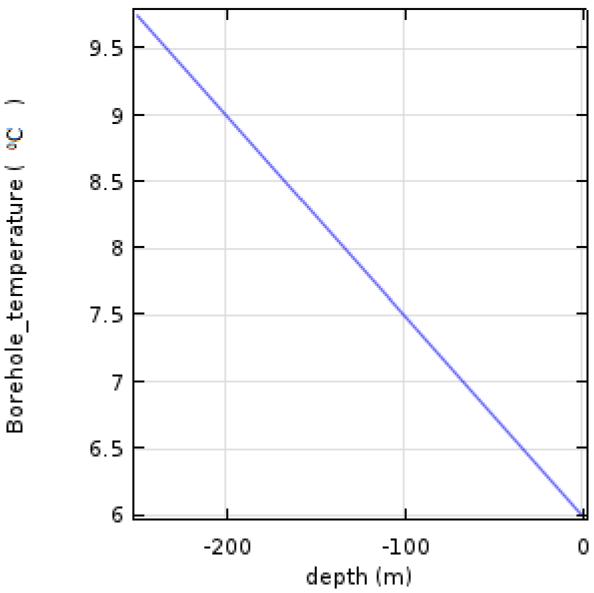

Fig. 3. Initial temperature of the borehole.

Peak load is 60 kW, six hours every day in Fig. 4. The heat pulse is periodic and continuous for the whole time duration of four months. Applying all these conditions to the model, mean fluid temperature entering heat pump is presented in Fig. 5. The maximum incoming fluid temperature to the heat pump is above 8 0C and the minimum fluid temperature is calculated to be a bit below 0 0C. Special carrier fluid is essential in this case, which has a freezing point well below 0 0C. The outgoing fluid temperature from the heat pump is shown in Fig. 6. Minimum temperature leaving the heat pump is about -7 0C, which a worst case. In this condition, the entering water temperature is seen to be below 0 0C, which results into a very low COP of the heat pump.

Table 1. Parameters used in simulation model

Parameter	**Symbol**	**Value**
Diameter of the pipe	d_pipe	35.2 mm
Flowrate	q	1 l/s
Heat pump capacity	power	60 kW
Depth of GHE	depth	250 m
Geothermal gradient	Tz_depth	0.015 K/m
Thermal conductivity of the ground	k_g	3.4 W/m.K
Initial ground temperature	T_0	6 ^{0}C

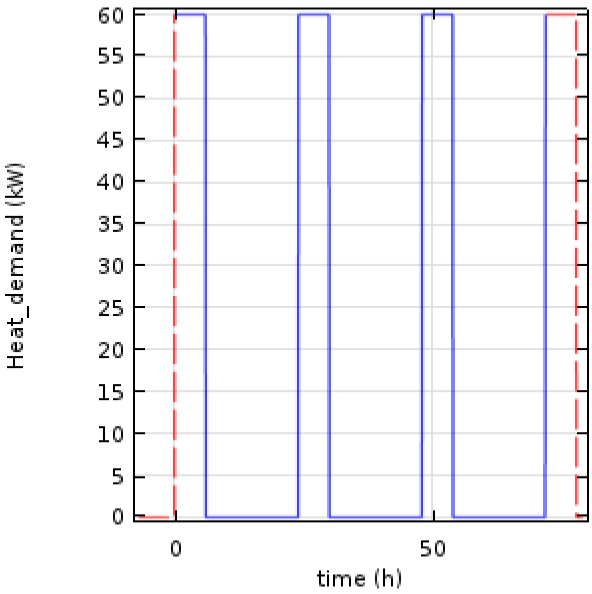

Fig. 4. Heat demand pulse (6 hours every day).

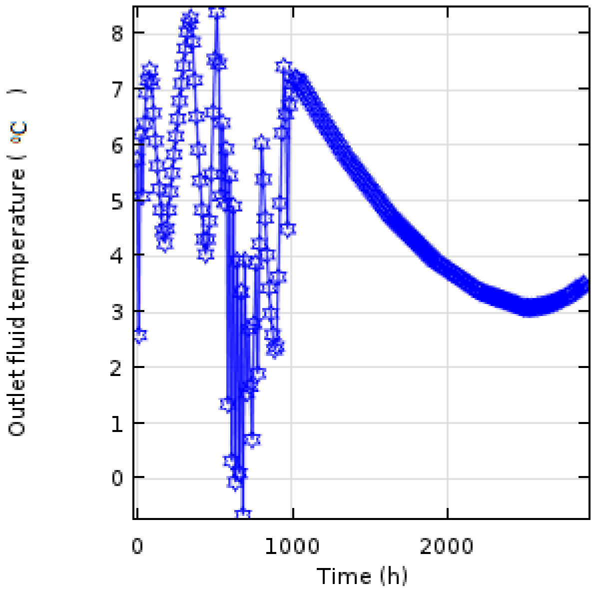

Fig. 5. Inlet fluid temperature to the heat pump (which is the outlet fluid temperature from the GHE).

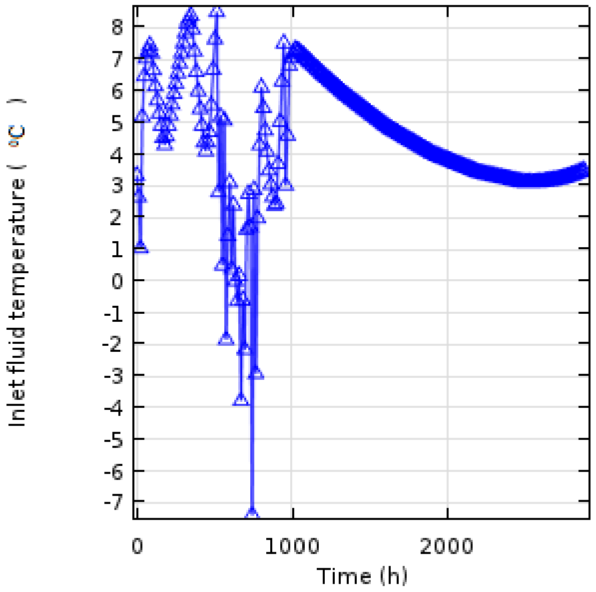

Fig. 6. Outlet fluid temperature from the heat pump (which is the inlet fluid temperature to the GHE).

Temperature change inside the borehole is presented in Fig. 7. Maximum and minimum borehole temperature may be achieved to 10 0C and -4 0C. Average temperature is also presented which is ideal for heat transport to carrier fluid. Multiple lines are predictions during the simulation time from first hour until 2880 hours. In Fig. 8 shows the effect of varying length on the performance of the heat pump. Simulations with 250 m length of the borehole which gives probably the least plausible values of the entering water and leaving water to and from the heat pump. Performance of a 60 kW heat can easily be observed with the COP, which gives a value of 1, means no renewable energy is being generated, necessitate to increase the length of the borehole.

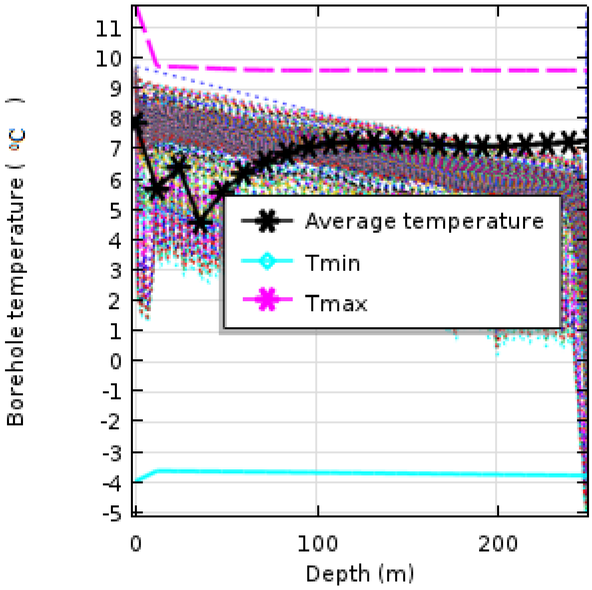

Fig. 7. Temperature of the borehole during the operation time of four months. (Maximum, minimum and average temperature).

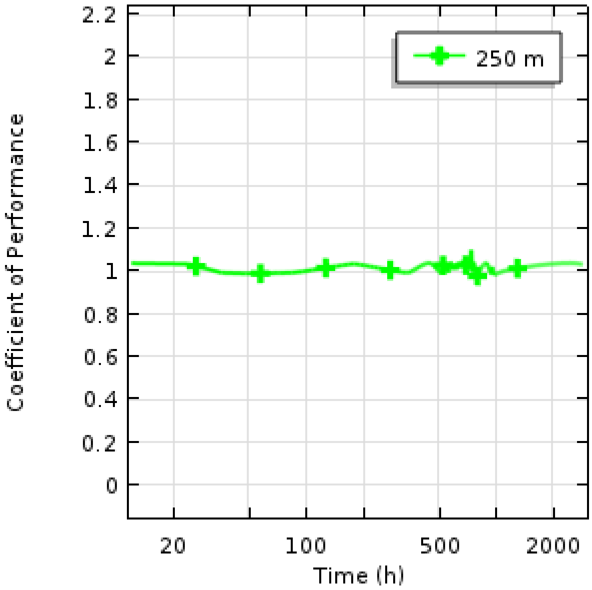

Fig. 8. Coefficient of Performance of the heat pump.

Laitinen et al., (2014) suggested 0 0C average ground source temperature with a peak-to-peak amplitude of 2 0C in a study took place at VTT (Finnish government agency for research). It must be noted that borehole is insulated from the surface in order to avoid much influence from the air temperature plus to mitigate heat losses from the surface. This simulation did not assume any insulation on surface ground. This simulation test analyse the underperformance of a heat pump in the existing system for which an increase in the length of the borehole is essential to generate renewable energy, improve the COP, so to reduce the energy consumption of the building. Next section is dedicated to find the optimal length of the GHE and suggest an improvement on the existing method.

3 GHE optimal length calculation

The heat transfer between the borehole wall and the neighboring soil involves thermal resistance of the borehole and the ground. The relation between the amounts of heat that has been injected/extracted from the ground is expressed as the following (Hellström, 1991 and Eskilson, 1987):

$$T_g - T_f = q'R_b \tag{1}$$

Here, q represents the amount of power extracted from the ground each unit meter, R_b is thermal resistance of the borehole which conceals the convection and conduction heat transfer in the heat exchanger pipe, T_f and T_g are the temperature of the surrounding ground and the fluid inside the heat exchanger pipe. Deriving eq. (1) for length:

Since,

$$q' = \frac{Q}{L} \tag{2}$$

Eq. (1) =>

$$T_g - T_f = \frac{Q}{L} R_b \tag{3}$$

$$L = \frac{QR_b}{T_g - T_f} \tag{4}$$

Where, T_f is the mean fluid temperature which can be construed as following (Kavanaugh, 2010):

$$T_f = \frac{T_{in} - T_{out}}{2} \tag{5}$$

Substituting eq. (5) into eq. (4):

$$L = \frac{QR_b}{T_g - \frac{T_{in} - T_{out}}{2}} \tag{6}$$

Eq. (6) has been used numerically to find the length of the borehole with some variations. Two methods that are frequently used worldwide are IGSHPA and ASHRAE.

2.1 IGSHPA

As it is obvious from the name of this method, IGSHPA provides a method to find the length of the borehole heat exchanger which is the source for a heat pump. This method utilizes eq. (6) in a way that ground heating or cooling capacity of the heat pump is taken into account along with additional factors such as run time fraction of the heat pump, thermal resistance of the ground and borehole. Instead of using mean fluid temperature of borehole heat exchanger pipe, minimum entering and leaving water temperature is considered in the denominator. The heat capacity in eq. (7) is the maximum heat capacity of the heat pump which is converted to ground load by multiplying with the coefficient of performance. Thermal resistances are calculated independently of time, consist of information of the shape factor of the U-tube heat exchanger and the inner and outer diameter of the pipe. Borehole heat exchanger length is expressed as following:

$$L = \frac{Q\left(\frac{COP-1}{COP}\right)(R_b+R_g F_h)}{T_g - \frac{EWT_{min}+LWT_{min}}{2}} \tag{7}$$

Where, Q is the maximum heat capacity of the heat pump, COP is the coefficient of performance, R_b and R_g is thermal resistance of the borehole and ground respectively, F_h is run fraction, T_g, EWT_{min} and LWT_{min} are temperature of the ground, entering and leaving water to the heat pump.

2.2 ASHRAE

The first ASHRAE sizing method appeared in Kavanaugh & Rafferty (1997) with a detailed analysis of a heat pump during the design month, which later improved by Bernier (2006) expressed in eq. (8). Three ground load pulses are taken into account to find the optimal length of the borehole heat exchanger. Heating and cooling load pulses can be determined with any synthetic load calculation. Thermal resistance on the other hand, is calculated using the g-function from Eskilson (1987). This method is further expanded in the work of Philippe & Bernier (2010) with the variation of calculating thermal resistances. The expression is presented as:

$$L = \frac{q_h R_b + q_y R_y + q_m R_m + q_h R_h}{T_g - \frac{T_{wi}+T_{wo}}{2} - T_p} \tag{8}$$

2.3 Proposition

Both of the methods calculate the length of the borehole heat exchanger for ground source heat pump. Thermal conductivity of the ground and borehole in both methods. Study includes ground source heat pump which has a source, for now, 250 m borehole heat exchanger depth. Analyzing this scenario with simulation, finding the optimal length and thermal response of the neighboring ground of the borehole heat exchanger is given a priority. Expanding the eq. a results:

$$L = \frac{q_h R_b + q_y R_y + q_m R_m}{T_g - \left(\frac{T_{in}+T_{out}}{2}\right)} \tag{9}$$

Where, q_h, q_m and q_y are the maximum heat capacity of the heat pump, the highest monthly load and the yearly load respectively. T_g, T_{in} and T_{out} are the temperature of the ground, inlet and outlet fluid temperature of the heat pump. L represent the length of the GHE in eq. (9) and thermal resistance of the borehole is shown with steady state, time-dependent yearly and monthly pulses R_b, R_m and R_y respectively. Previous methods calculated thermal resistance either using the Fourier g-function (Kavanaugh, 2010) or Eskilson g-function (Bernier, 2006 & Eskilson, 1987). In this study, thermal resistances are calculated without g-function, instead time-dependent thermal resistance for heat extraction is borrowed from Eskilson (1987) expressed as:

$$R_t = \frac{1}{4\pi k}\left[\ln\left(\frac{4at}{r_b^2}\right) - \gamma\right] \tag{10}$$

Where, t is the time period in hours, rb is borehole radius, a is thermal diffusivity, k is the thermal conductivity of the ground and γ is the Euler constant. Time period for calculating the yearly and monthly thermal resistance should be converted into hours. Steady state borehole resistance may be calculated with the shape of the heat exchanger pipe. Eq. (10) does have a restriction of the time period pulse, it varies between few hours to few years. Hourly thermal resistance is excluded from eq. (9) which has been used in the previous studies for this very reason.

An optimal length of the GHE may be calculated for the existing system which has a 60 kW maximum heat capacity of the heat pump. In the practical case, heating demand is given as energy consumption of a building, which is 432.3 MWh. Monthly heating load may be calculated as presented in Table. 2, which represents heating demand for each month from January to December. Suitable heat capacity for current demand should be met with a 60 kW heat pump. Ground load can be estimated with the using the COP of 4 which desired, which led to the estimation of monthly, yearly and hourly load.

Table 2. Monthly heating load for 432.3 MWh

Month	Heat Load (kW)	Peak Load (kW)
Jan	6.393	45
Feb	6.105	45
Mar	5.156	45
Apr	4.083	45
May	2.640	11.25
Jun	0	0
Jul	0	0
Aug	0	0
Sep	2.516	11.25
Oct	3.588	45
Nov	4.826	45
Dec	5.940	45

$q_y = 55000, \quad q_m = 6393, \quad q_h = 60000 \ (kW)$ &,

$R_b = 0.1, \quad R_y = 0.1898, \quad R_m = 0.1339 \ (m.K/W)$

Time-dependent thermal resistance for extraction is calculated using eq. (10), the borehole thermal resistance may be calculated with existing methods considering shape factors and configuration of heat exchanger pipe (either U-tube or Co-axial) (e.g., Hellstrom, 1991). Ground temperature in Finland is evidently around 8 ^{0}C (Hakala et al., 2014). Average Inlet and outlet temperature of the heat pump in Finland is recommended to be 0 ^{0}C (Laitinen, et al., 2014). After putting all the above mentioned values in eq. (9), an optimal length of GHE may be estimated. Length of the borehole is presented in Table. 3, along with the comparison to IGSHPA and spreadsheet from ASHRAE (Narsilio et al., 2014 and Philippe & Bernier, 2010).

Table 3. GHE optimal length comparison

Method	Length (m)
Proposed Eq. (9)	2162
IGSHPA	19851
Philippe & Bernier (2010)	2189

4 Results and discussions

Length of GHE calculated with eq. (9) used strict ground load that are estimated using yearly and monthly heating demand and given maximum capacity of the heat pump. It may be so, these ground load calculated with a synthetic load function or statistical data from an existing load of a similar building. Thermal resistance may be calculated with either of the g-functions available or with Eskilson, (1987) time-dependent resistance, in which case, hourly resistance must be eliminated from eq. (9). IGSHPA method rely totally on the steady state values. Thermal resistances are calculated with consideration of the shape factor of the heat exchanger pipe and the steady state ground and borehole. Convection heat transfer is neglected which plays an important role in heat transfer in pipes. Instead a run fraction of the heat pump is added in the calculation. Length of GHE is calculated with multiple try with different entering and leaving water average temperature to and from the heat pump.

Second approach to estimate the length of GHE consider the effective thermal resistances for multiple ground load pulses. Another parameter is involved for multiple borehole configuration, the so called, “temperature penalty”. This constrain rises due to interference between boreholes. Temperature penalty is calculated using a correlation function. ASHRAE method takes convection heat transfer coefficient into consideration and fluid thermal properties as well. Thermal resistance is suggested to be estimated using either Fourier’s g-function or Eskilson’s g-function. In the original steady state form of eq. (9), heat load is the extraction rate. This rate has been classified differently in both of the methods. A closer look would suggest that in all of the hourly, monthly and yearly heat load are being fractioned through thermal resistance, and basically, some fraction of the total load is put to calculate the optimal length of the borehole. Time management of the estimated load may provide even better results than the existing ones. Since the heat pump does not run during the whole day except for winter in a harsh climate, suggesting to simulate heat load for length optimization with various time periods when weather allows inconsistency of the heat pump run time.

The estimated length of the borehole is found to be 2162 m. It is not practical to have one borehole with a huge depth. Instead it should be divided into multiple boreholes. This length may be divided into nine boreholes with 240 m length so to make it practical. Since this suggests a small configuration of 3x3 boreholes. Thermal interference in this case is neglected and 2D thermal response of the boreholes presented in the next section showing the temperature difference after few years of extraction. Next section simulate the optimal length of borehole configuration in 2D, thermal response of the borehole at a point is presented and the exponential decrease of borehole temperature is depicted using line source.

5 Analysis of the GHE using the optimal configuration

In order to observe thermal response of the neighboring ground, a 3x3 GHE configuration is chosen which fulfills the criteria of the optimal length. Thermal interference is minimum and presented in Figs. 9, having simulation time duration varying from 1st month to 5 and 10 years.

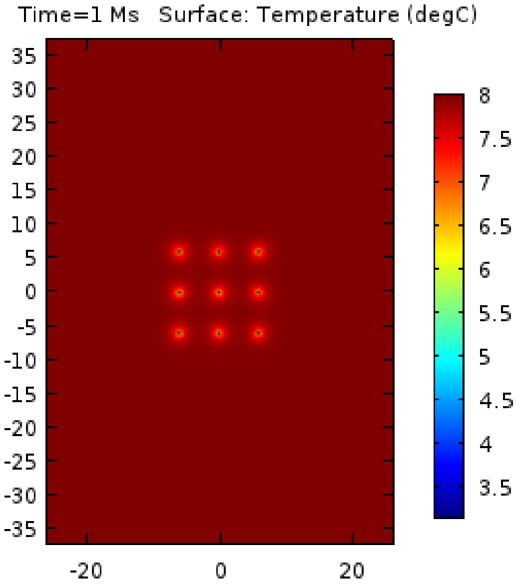

Fig. 9. (a) Surface temperature after one month of heat extraction

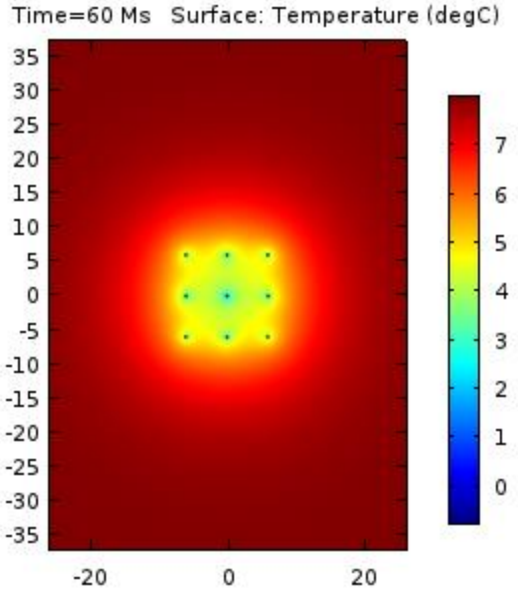

Fig. 9. (b) Surface temperature after five years of heat extraction

Simulation represents the surface temperature of the ground during the time span of constant extraction. The heat extraction rate is equally divided with respect to the calculated length of the GHE and applied on every borehole. Initial temperature of the ground is assumed to be 8 0C. The average monthly air temperature is applied on the surface of the ground as shown in Fig. 2. The simulation time duration is selected to be five years during which the temperature decay in the boreholes can be observed from Fig. 9, in which heat transfer is taken place in the direction of x-axis, depicting the thermal interaction between the boreholes. This representation only gives an idea of what the temperature of the boreholes might be after the process of extraction for years.

A point temperature is presented in Fig. 10 showing a monthly temperature decay in the boreholes at an arbitrary point. Only one point is taken into account because all the boreholes are symmetric in nature. After ten years of operation, the temperature decrease down to -1 0C. Result is being compared with the very conventional line source model (Ingersoll et al., 1954). Multiple simulations are performed using different inlet fluid temperature to see the thermal response at the outlet presented in Fig. 11.

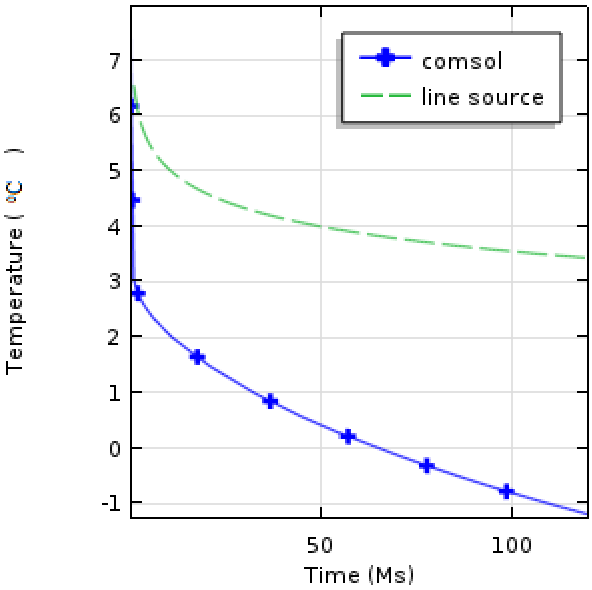

Fig. 10. Arbitrary point temperature of the borehole.

The estimated outlet fluid outlet temperature lead to calculate the improved COP after the system has been enhanced. COP for multiple entering and leaving water temperature to and from the heat pump is presented in Fig. 12. Improvement of the performance of a heat pump is shown with the COP. If the value of COP is 2, it means, energy consumption of the heat pump is half and renewable energy production of the heat pump is half as shown for LWT=2 0C. The best case scenario is when the temperature of the leaving water from the heat pump is 0 0C, which is the recommended average value for Finland. It should be very well understood that, very precise information on the performance of the GSHP system requires a combined simulation of all the boreholes, instead in this simulation, only one borehole is assumed to be fulfill the criteria, since homogeneous condition is assumed in this case. But multiple boreholes may be assumed for a more precise system response simulation with different thermal properties.

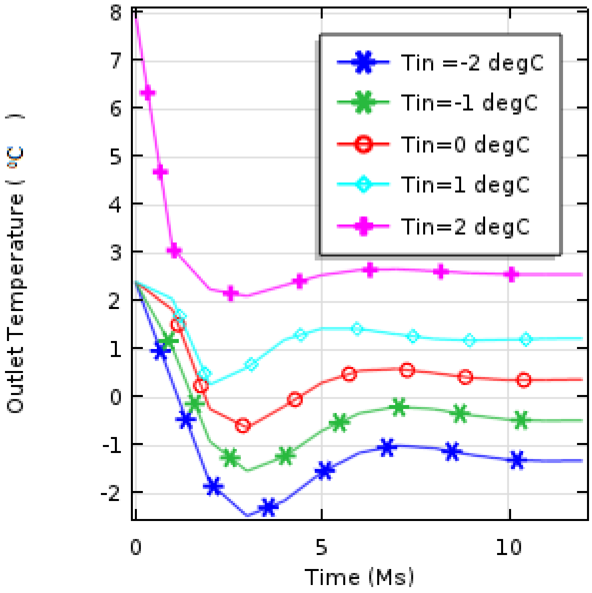

Fig. 11. Outlet temperature using multiple inlet fluid temperature.

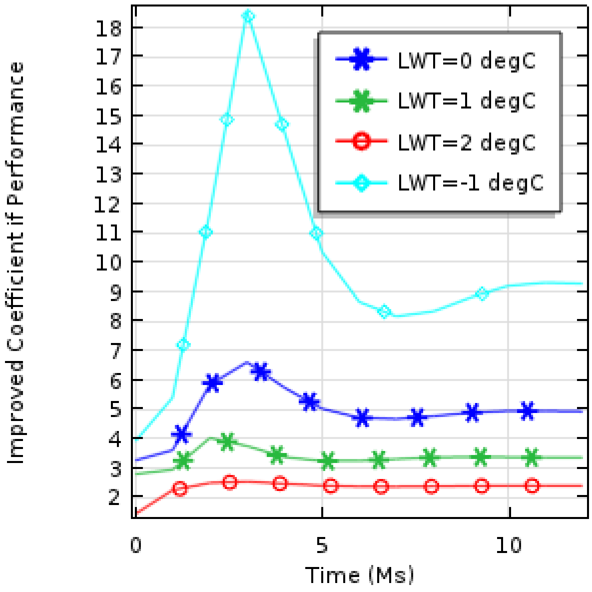

Fig. 12. Improved COP for optimal length of GHE.

6 Conclusion

An applicable method is presented in this study to find the length of GHE for GSHP. The importance of this study is to produce an easy method to analyze first, the current situation closely, get all the necessary tools to meet the required criteria and execute with the improved values to configure a better geothermal system. A 60 kW heat pump performance has been realized. The short coming measure to impede the performance of the GSHP has been identified. It has been observed that the length of the GHE is not optimal for the heat pump to operate with the maximum efficiency. This problem has been shown to be remediated with the help of modeling and simulation by increasing the length of GHE. A method has been presented to perform that task along with the comparison of the existing methods. Simulations are performed with the improved length to show the thermal response of the boreholes. For this purpose, conventional line source method has been adopted to utilize for the very purpose of comparing the simulated thermal response using Comsol and line source. Results have been presented for a time duration of ten years. Thermal interaction between boreholes have been presented in 2D for multiple years. In the end, simulations are performed once again using multiple values of inlet temperature at the heat exchanger pipe, finding the outlet temperature for the period of one year by applying the average air temperature of Finland at the surface of the ground. COP is presented with the improved performance of the heat pump after enhancement in the length of GHE. Simulations are carefully under taken, since, it may reflect a practical case with an approximate results as presented in this study.

Acknowledgement

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NOMENCLATURE

Q	Capacity of the heat pump (W)
COP	Coefficient of performance
R_b	Borehole resistance (m.K/W)
R_g	Ground resistance (m.K/W)
R_m	Monthly borehole resistance (m.K/W)
R_y	Yearly borehole resistance (m.K/W)
F_h	Run fraction
T_g	Undisturbed ground temperature (^{0}C)
EWT	Entering water temperature (^{0}C)
LWT	Leaving water temperature (^{0}C)
L	Length of borehole (m)
kg	Thermal conductivity of the ground (W/m.K)
t	Time duration of the simulation (hours)
α	Thermal diffusivity (m^2/s)
r	Radius of the borehole (m)
T_0	Initial temperature of the ground (^{0}C)
T_f	Fluid temperature (^{0}C)
T_{in}	Inlet temperature (^{0}C)
T_{out}	Outlet temperature (^{0}C)