IMPACT OF SOIL TEMPERATURE VARIATION ON PERFORMANCE MODELING OF A NOVEL SHALLOW BORE GROUND HEAT EXCHANGER

Liang Shi[1], Ming Qu[1], Xiaobing Liu[2], and Mingkan Zhang[2]
[1]Purdue University, West Lafayette, IN, USA
[2]Oak Ridge National Laboratory, Oak Ridge, TN, USA

ABSTRACT

A novel shallow bore (< 6 m deep) ground heat exchanger is proposed to substitute the conventional vertical bore ground heat exchanger (> 60 m deep) for ground source heat pump systems. A series of simulations were carried out to evaluate the impacts of the vertical soil temperature profile on the performance of the shallow bore ground heat exchanger in response to thermal loads of a ground source heat pump system, with various lengths of the shallow bore ground heat exchanger and ground thermal properties. The results indicate that the vertical soil temperature profile has a noticeable influence on the thermal response of the shallow bore ground heat exchanger. Moreover, for shallow bore ground heat exchangers with the same volume and buried depth, the one with greater length and narrower diameter has lower tank water temperature fluctuations over the year due to relatively more stable soil temperature, and the larger surface to volume ratio.

INTRODUCTION

The ground source heat pump (GSHP) is an energy-efficient technology for space heating, cooling, and air conditioning. Approximately 5.7 quadrillion BTUs of primary energy can be saved annually in the United States by retrofitting existing heating and cooling systems with GSHPs (Liu et al. 2019). The high efficiency of GSHPs is a result of the favorable subsurface temperature of the ground, which is cooler than the ambient air in summer but warmer in winter. However, the adoption of GSHPs in the United States is currently still limited due to their high cost of installation. The ground heat exchanger (GHE), which is used for heat exchange with the surrounding ground formation, accounts for about 30% of the total installation cost of a GSHP system (NYSERDA 2017).

The most commonly used GHE in the United States is the vertical bore ground heat exchanger (VBGHE), and the expensive drilling required to create the vertical borehole is the primary factor contributing to the high cost of VBGHE installation (Liu et al. 2018). The horizontal ground heat exchanger is another common method for exchanging heat with the ground. A horizontal ground heat exchanger consists of straight or spiral pipes buried just a few feet below the surface, and it can provide similar performance as the VBGHE (CDH 2017, Im et al. 2012) but with a lower cost. However, horizontal ground heat exchangers require a large land area and significant excavation to install.

To address the economic challenge of the VBGHE, researchers have explored several new shallow bore ground heat exchangers (SBGHE) in recent years. One example of the SBGHE is the basket heat exchanger. A basket heat exchanger consists of a helical coil wrapped around supporting rods and buried in a shallow borehole, which is 8 m deep and with a 0.26 m diameter. Field tests of the basket heat exchangers showed that the heat transfer of the basket heat exchangers is highly sensitive to the thermal conductivity of the backfill material and the surrounding soil (Bertermann et al. 2018). Another kind of SBGHE is GeoColumn. It utilizes a shallow tank (6 m long with 0.76 m diameter), filled with water and buried in the ground, to exchange heat with the surrounding soil. A heat exchanger coil transfers heat from a refrigerant to the tank. The water in the tank provides a larger heat capacity than the conventional VBGHE. The most recently developed SBGHE is the underground thermal battery (UTB), which was introduced by the researchers from Oak Ridge National Laboratory (Zhang et al. 2019; Warner et al. 2020). A UTB is comprised of a tank filled with water buried in the shallow subsurface of the ground (less than 20 ft or 6 m deep), a helical heat exchanger immersed in the center

This manuscript has been authored in part by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

of the tank and connected to a water source heat pump, and a small amount of enclosed phase change materials (PCMs), suspended in the annulus between the heat exchanger and the tank wall to provide the additional thermal capacity to the tank. A unique "water chimney" design utilizes the vertical temperature gradient of the heat exchanger coil (warm at the bottom and cold at top) to promote natural circulation within the tank, increasing the heat transfer between the tank water and the surrounding soil, heat exchanger coil, and the PCM, while maintaining a relatively uniform tank temperature. The tank has a large heat capacity due to the sensible heat of the water and the latent heat of the PCM. It is a good buffer to the instant high thermal load, and can effectively stabilize the outlet temperature from the coil heat exchanger. The heat absorbed by (or extracted from) the water and the PCM can dissipate into (or be recovered from) the ground through the tank wall.

The soil temperature is affected by the ambient temperature, so it swings around the annual average temperature over a year. However, the fluctuation of the soil temperature decreases drastically with the depth of the soil, as shown in Figure 1. The temperature of the soil between about 9 m (30 ft) and 122 m (400 ft) below the ground usually does not change during a year at a given location.

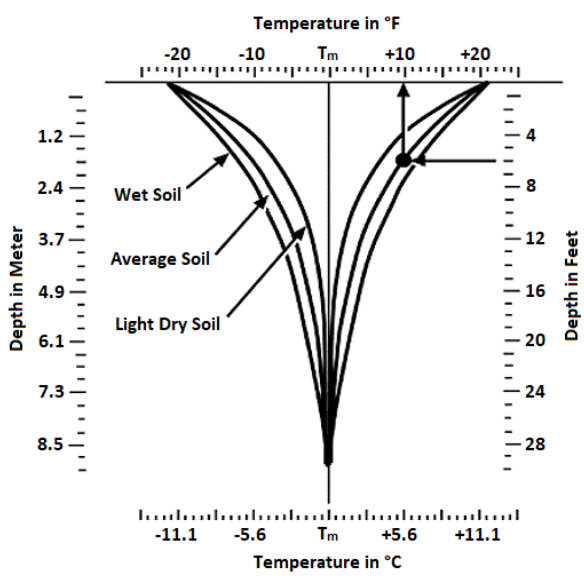

Figure 1. Temperature distribution in the subsurface of the soil (Bose, 1985)

Some numerical models of VBGHEs apply uniform soil temperature as a boundary condition, and also ignore the heat transfer through the ground surface because their depths are usually higher than 60 m. However, it is questionable whether this practice fits for modeling an SBGHE, which could be shorter than 6 m (20 ft). This study investigates the impacts of the vertical soil temperature profile and the ground surface heat flux on the temperature change of a simplified UTB (without using PCM) in response to thermal loads of a GSHP system.

METHODOLOGY

A two-dimensional (2D) numerical model of the surrounding soil of a UTB has been developed to account for both the ground surface heat flux and the vertical temperature gradient in the soil. The 2D model was validated against the results predicted by a comprehensive 3D model of the UTB and the surrounding soil. The 2D model was then used to predict the tank water temperature of the simplified UTB in response to a whole year (8760 hours) of thermal loads from a GSHP system under two conditions: (1) with a uniform undisturbed soil temperature which is constant year-round and zero heat flux at the ground surface (named as 'uniform soil temperature' condition), and (2) accounting for the seasonal variation of the undisturbed soil temperature along with the depth of the soil and the dynamic heat flux on the ground surface (named as 'variable soil temperature' condition).

The simulation predicted tank water temperature under the two conditions were compared to evaluate the difference resulting from the two conditions. Furthermore, a parametric study was conducted to investigate the impacts of the two conditions on the tank temperature with various UTB dimensions.

2D Numerical Model

According to the past study (Warner et al. 2020), the water temperature in the UTB was nearly uniform due to natural convection in the tank, so the tank was modeled as a column-shape water bulk with uniform temperature. The UTB has two external heat sources: (1) the thermal load injected to the tank, which is from a GSHP system; and (2) the heat flux at the UTB boundary—the interfaces between the UTB and the surrounding soil.

A 2D finite-difference model under the cylindrical coordinate has been developed to simulate the soil surrounding a UTB. Differential equation under cylindrical coordinate for 2D unsteady heat conduction without internal heat gain can be expressed, as shown in Equation 1.

$$\rho_s c_{p,s} \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \cdot k_s \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_s \frac{\partial T}{\partial z}\right), \qquad (1)$$

where ρ_s is the soil density, $c_{p,s}$ is the soil specific heat, T is the soil temperature, t is time, r is radius position, k_s is the soil thermal conductivity, and z is the depth.

Discretize the above differential equation with the explicit method and re-organize it, we can get Equation 2.

$$T_{i,j}^{new} = T_{i,j} + \frac{\Delta t}{\rho_s c_{p,s}} \cdot \frac{1}{r_j} \cdot \frac{1}{\Delta r}\left[\left(r_j - \frac{1}{2}\Delta r\right) \cdot k_s \frac{T_{i,j-1} - T_{i,j}}{\Delta r} - \left(r_j + \frac{1}{2}\Delta r\right) \cdot k_s \frac{T_{i,j} - T_{i,j+1}}{\Delta r}\right] + \frac{\Delta t}{\rho_s c_{p,s}} \cdot \frac{1}{\Delta z}\left(k_s \frac{T_{i-1,j} - T_{i,j}}{\Delta z} - k_s \frac{T_{i,j} - T_{i+1,j}}{\Delta z}\right), \quad (2)$$

where the subscript *i* and *j* corresponds to the parameters in the radial direction and the vertical direction, respectively.

The simulation domain and boundary conditions for the baseline case are shown in Figure 2. The simulation domain along the radial direction is from the centerline of the tank to a distance which is 20 times the UTB tank radius. Along the vertical direction, the simulation domain is from the ground surface to a depth of 30 m. The UTB is buried at a certain distance below the ground surface. For the soil meshing, along the radial direction, the increment is 9.5 cm, and along the vertical direction, the increment is 10 cm.

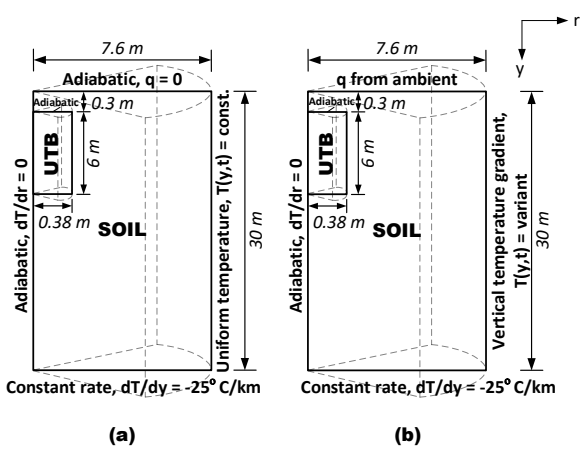

Figure 2. Simulation domain and boundary conditions for the baseline case (not drawn to scale). (a) 'uniform temperature condition, (b) 'vertical temperature gradient' condition

The boundary condition at the ground surface is either adiabatic ('uniform temperature' case) or the net heat flux from the ambient or canopy layer ('vertical temperature gradient' case). The boundary at the bottom of the soil domain is affected by the conduction heat flow from the cell above it and the geothermal heat flux from the earth's core. A typical value for the geothermal gradient of 25ºC/km is used as suggested by Fridleifsson et al. (2008). Besides, other boundaries within the simulation domain are assumed as: along the vertical centerline of the UTB is adiabatic; the outer boundary of the soil domain in the radial direction is either the undisturbed soil temperature ('vertical temperature gradient' condition) or uniform temperature ('uniform temperature' condition); between the upper surface of the UTB and the soil is adiabatic.

Ground Surface Heat Fluxes

The vegetation above the ground surface was simulated as a canopy, which influences the solar radiation to the ground (Xing and Spitler, 2017). The canopy layer was assumed to have negligible thermal mass. Therefore the net heat gains at the canopy layer were zero and it was a function of the canopy temperature. The energy balance for the canopy layer can be expressed as Equation 3.

$$q_{solar,f} + q_{rad,sky,f} + q_{rad,g,f} - q_{rad,f,sky} - q_{rad,f,g} - q_{conv,f} - q_{evap,f} = 0, \quad (3)$$

where $q_{solar,f}$ is the short-wave solar radiation absorbed by the canopy layer; $q_{rad,sky,f}$ is the long-wave thermal radiation from the surrounding to the canopy layer; $q_{rad,g,f}$ is the long-wave thermal radiation from the ground surface to the canopy; $q_{rad,f,sky}$ is the long-wave thermal radiation from the canopy layer to the surrounding; $q_{rad,f,g}$ is the long-wave thermal radiation from the canopy layer to the ground surface; $q_{conv,f}$ is the convective heat loss through the canopy to the surrounding air; and $q_{evap,f}$ is the heat loss through evaporation from the canopy to the surrounding air. Explanations and expressions for these terms are elaborated by Xing and Spitler (2017). The TMY3 weather data (Wilcox and Marion, 2008) was applied, and the ground surface heat fluxes can be determined according to Equation 3.

Initial Conditions

The initial temperature of the UTB tank water is the typical municipal water temperature when the tank is first filled with the municipal water (e.g., at 17ºC). For the 'uniform temperature' condition, the initial soil temperature is uniform at the annual average of the undisturbed ground temperature at a given location. For the 'variable soil temperature' condition, the initial soil temperature was determined with the following calculations.

A two-order harmonic model recommended by Xing and Spitler (2017), as shown in Equation (4), was used to determine the undisturbed soil temperature at any day of a year and at any specified depth (within a certain range). The parameters for the model can be determined either from the measured data or from the simulation results of the numerical model described in the previous subsection.

$$T_s(z,t) = T_{s,avg} - \sum_{n=1}^{2} e^{-z\sqrt{\frac{n\cdot\pi}{\alpha_s\cdot t_p}}}\, T_{s,amplitude,n} \cdot \cos\left(\frac{2\pi\cdot n}{t_p}(t - PL_n) - z\sqrt{\frac{n\cdot\pi}{\alpha_s\cdot t_p}}\right), \quad (4)$$

where $T_s(z,t)$ is the undisturbed soil temperature at a given depth and time of the year, in ºC; z is the soil depth, in m; t is the time of the year, starting from January 1, in days; $T_{s,avg}$ is the annual average ground temperature, in ºC; α_s is the soil diffusivity; in m^2/day;t_p is the period of the soil temperature cycle, in days; $T_{s,amplitude,n}$ is the nth order temperature amplitude, in ºC; PL_n is the nth phase lag of the ground temperature cycle, in days.

The calculated undisturbed soil temperature over a year at a site in Knoxville, TN is shown in Figure 3. The undisturbed soil temperature profile on the first day of the annual simulation was used as the initial condition of the simulation domain of the soil.

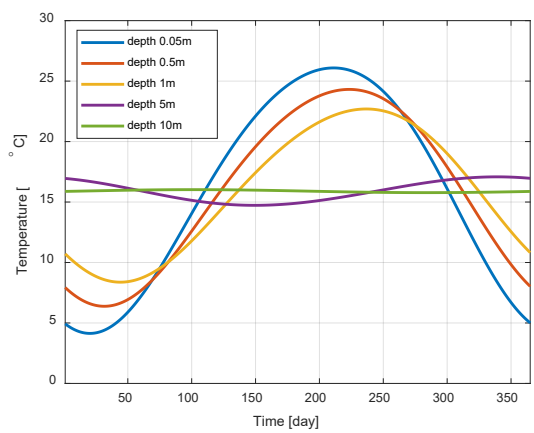

Figure 3. Calculated undisturbed soil temperature over a year at a site in Knoxville, TN

MODEL VALIDATION

A three-dimensional (3D) numerical model of the SBGHE was developed using commercial software, ANSYS/FLUENT (version 17.2), and validated with experimental data (Zhang et al. 2019). The tank temperature predicted by the 2D model was compared with that predicted by the 3D model.

The dimensions and the thermophysical properties of the simulated UTB are listed in tables 1 and 2.

Table 1 Dimensions of the simulated UTB

Tank length [mm]	6,710
Tank diameter [mm]	760
Soil depth [mm]	7,930
Soil diameter [mm]	7,620
PCM thickness [mm]	80
PCM length [mm]	4,470
Heat exchanger coil outer diameter [mm]	28.85
Heat exchanger coil inner diameter [mm]	22.45
Helical diameter of heat exchanger coil [mm]	381

Table 2 Thermal properties of materials used in UTB

	Soil	**Water**	**PCM**
Thermal conductivity [W/(m·K)]	1.72	0.6	1.09 (solid) / 0.54 (liquid)
Specific heat [J/(kg·K)]	2121	4182	3140
Density [kg/m^3]	1900	998	831.3
Melting point [K]	--	--	278
Latent heat [kJ/kg]	--	--	200

The tank water temperature of the UTB was predicted with the 3D model under the two conditions: (1) with the initial vertical temperature profile in the soil, and (2) with uniform initial soil temperature. For both conditions, the net heat flux at the ground surface was considered. The initial soil temperature profile on a typical winter day, February 14, at Knoxville, TN was calculated with the soil temperature model introduced above and it is shown in Figure 5. As can be seen in Figure 5, the soil temperature along the shallow bore where the UTB was installed is lower than 290 K (16.86°C), which is the annual average soil temperature (i.e., the assumed uniform initial soil temperature).

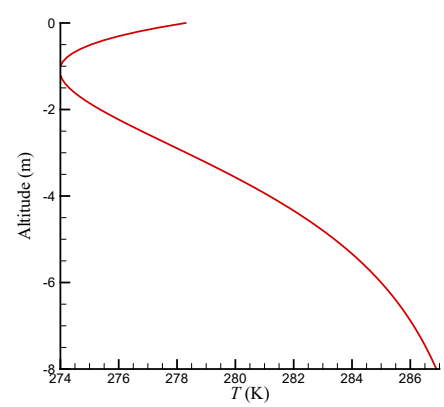

Figure 4. Initial soil temperature along with the depth of soil on a typical winter day at Knoxville, TN

Other than the initial soil temperature, all the other conditions were the same in the two cases. In the simulations, a constant heat extraction load of 2,528 W was imposed on the UTB continuously for 72 hours. The simulation predicted tank temperatures under the two conditions are shown in Figure 5. The simulation results indicate that the tank water temperature dropped more quickly under the condition with the initial soil temperature profile being accounted for than in the case with the uniform initial soil temperature. Figure 5 also reveals that temperature drop rates were slowed down for about 12 hours in the middle of the heat extraction operation in both cases, which was due to the solidification of the PCM. Note that tank temperatures did not change when they reached 273.15 K (0 °C) in both cases due to the freezing of water.

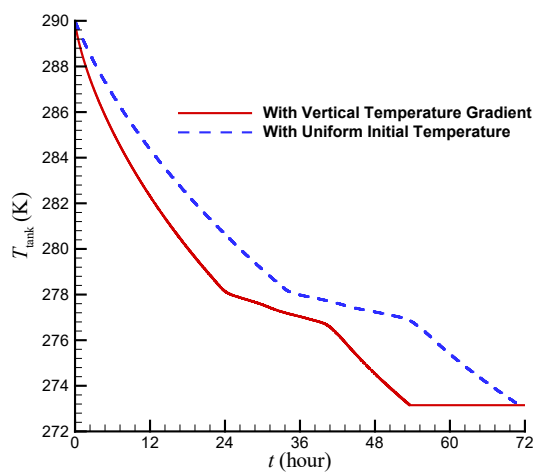

Figure 5. Comparisons of 3D model predicted tank water temperature under two conditions

The 3D model is too time-consuming to perform annual simulations with a reasonable time. Therefore, the 2D numerical model was used for the annual simulation. To avoid the complexity resulting from the thermal interaction between water and PCM, PCM was not modeled in this study and the UTB was simplified as a cylinder tank filled with water. The 3D model was revised to predict the tank temperature of the simplified UTB under the two conditions described earlier, and the results were compared with the predictions of the 2D model of the same UTB under the same two conditions. The results are shown in Figure 6, indicating a good agreement with each other. Therefore, the 2D model is used to simulate the annual performance of the UTB.

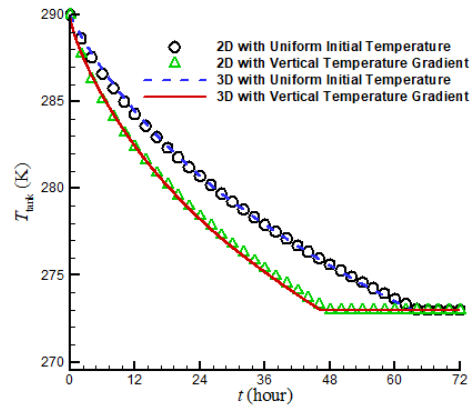

Figure 6. Simulation result comparison between 3D and 2D model of UTB

SIMULATION RESULTS

Thermal Loads of UTB

The hourly thermal load of the UTB during a year was generated with eQUEST, an integrated building energy simulation program, using a prototype residential building. The building is a single-family detached house located in Knoxville, Tennessee. A GSHP with 7 kW (2 cooling tons) capacity was applied to meet the cooling and heating demands of the building. Five identical and simplified UTBs (with 6.7 m tank length and 0.76 m tank diameter) were used as the heat sink and heat source of the GSHP in place of the conventional ground heat exchanger. The UTBs were installed 0.3 m beneath the ground surface and they were at least 6 m apart from each other to avoid thermal interaction among them. The hourly thermal load of each UTB throughout one year is shown in Figure 7. The thermal load includes both heat rejection (positive) and heat extraction (negative).

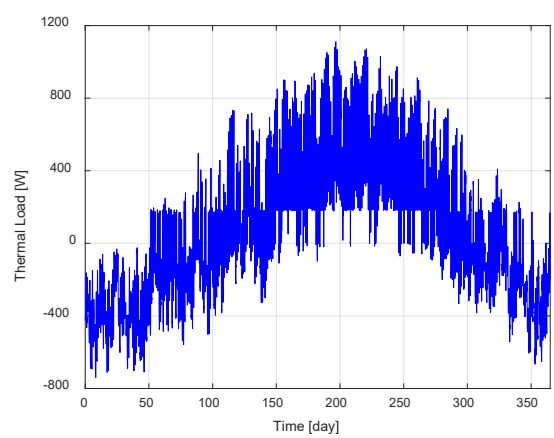

Figure 7. Hourly thermal load of a UTB during a year

Difference Resulting from the Two Conditions

With the above thermal load, the annual tank water temperature profiles of the simplified UTB under the two conditions are predicted using the 2D model and are shown in Figure 8. Figure 8 shows that the temperature fluctuation resulting from the variable soil temperature condition is larger than that from the other condition—about 5ºC lower minimum temperatures in winter and about 6ºC higher maximum temperatures in summer. The overall difference between the tank temperature profiles was quantified with the root mean square of the difference (RMSD) between the two tank temperatures at each hour. The calculated RMSD, in this case, was 3.6 ºC.

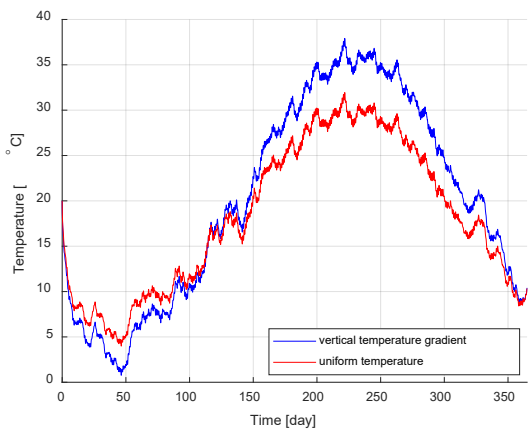

Figure 8. Comparison of tank water temperature profiles resulting from the two conditions

It indicates that the seasonal soil temperature variation along the UTB does affect the tank water temperature, which will, in turn, affect the efficiency of the GSHP. To assess the impact of this temperature difference on the power consumption of the GSHP, the annual power consumption of the GSHP resulting from the two tank water temperature profiles were determined based on the performance curves of a typical GSHP. The calculated annual power consumption resulting from the uniform soil temperature condition is 2,790 kWh, while it is 2,978 kWh under the condition of variable soil temperature. It means that the assumption of uniform soil temperature resulted in a 6% underestimation of the annual power consumption of the GSHP system, which is noticeable but not very significant.

Impacts of UTB Dimensions

A parametric study was conducted to investigate the impact of the two conditions on the tank temperature of UTBs with different dimensions. With different lengths of the UTB, the tank diameters were adjusted to keep all the investigated UTBs have the same volume. The thermal load to the UTB was adjusted to ensure the same heat transfer rate per unit surface area of the UTB at peak load condition. The dimensions of four different UTBs are listed in Table 3.

Table 3. Dimensions of UTBs with various lengths and identical volume

UTB	1	2	3	4
Length [m]	6	10	15	20
Diameter [m]	0.760	0.588	0.480	0.416
Heat Transfer Area [m^2]	14.8	18.7	22.8	26.3
# of UTB Needed	5	4	4	3
Surface-to-volume ratio [m^{-1}]	5.9	7.5	9.1	10.5

The tank water temperature profiles of the four UTBs under the two conditions were predicted with the 2D model and plotted in figures 9 and 10, respectively.

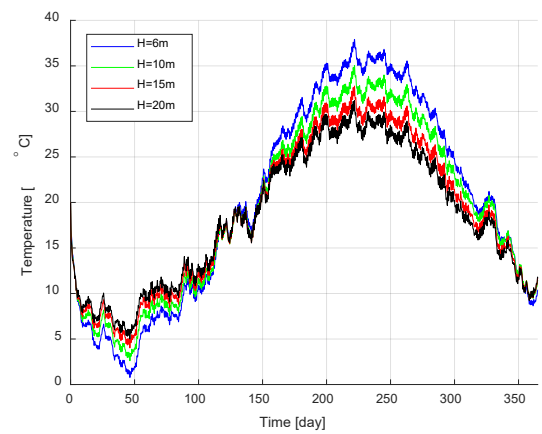

Figure 9. Tank water temperature profiles of four UTBs with identical volume under the variable soil temperature condition

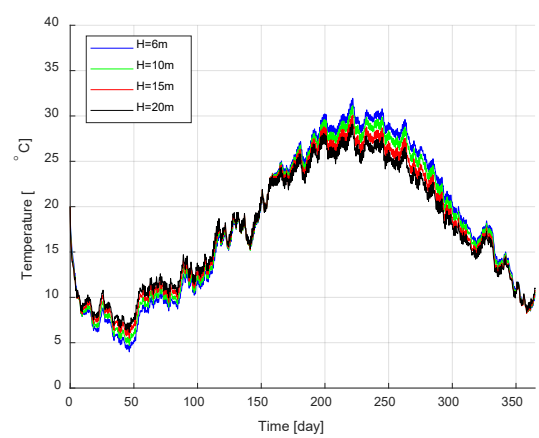

Figure 10. Tank water temperature profiles of four UTBs with identical volume under the uniform soil temperature condition

The above results show that, with the same volume and heat transfer rate per surface area, the longer UTB has less temperature fluctuation, which will result in higher efficiency of the GSHP. It is because that the longer UTB exposes to deeper soil, where the seasonal variation of the soil temperature becomes less, as depicted in figures 1 and 3. Besides, for the same volume, a longer length of a UTB increases the surface area and the surface-to-volume ratio, which helps to increase the heat exchange rate between the UTB and the surrounding soil. The average differences (quantified with RMSD) of the tank water temperatures of the four UTBs under the two conditions are plotted in Figure 11. The maximum tank temperatures of the four UTBs under the two conditions are shown in Figure 12.

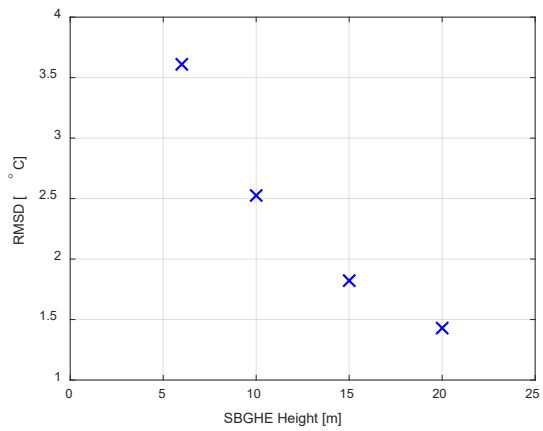

Figure 11. Average difference (RMSD) in predicted tank water temperature of the four UTBs with identical volume resulting from the two conditions

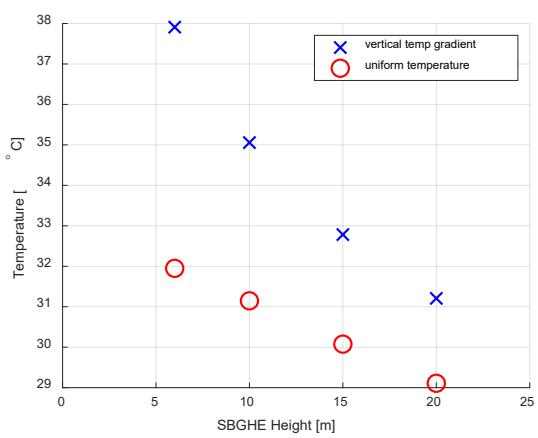

Figure 12. The predicted maximum tank water temperature of the four UTBs with identical volume resulting from the two conditions

Figure 11 shows that the RMSD decreases with the increase in UTB length. It indicates that the impact of the variable soil temperature is not critical for a UTB with 20 m or longer length (i.e., with an RMSD less than 1.5ºC). Figure 12 indicates that the maximum tank temperature was reduced significantly by increasing the length of the UTB under both conditions, which would improve the efficiency of the GSHP system. Furthermore, the differences between the maximum tank temperatures resulting from the two conditions decreased with the increase of the UTB length.

Another parametric study was conducted to investigate the impact of the two conditions on the tank temperature of UTBs with different heights but with the same heat transfer area. The dimensions of four different UTBs are listed in Table 4.

Table 4. Dimensions of UTBs with various lengths and identical heat transfer area

UTB	1	2	3	4
Length [m]	6	10	15	20
Diameter [m]	0.760	0.466	0.312	0.234
Volume [m^3]	2.50	1.57	1.05	0.79
Surface-to-volume ratio [m^{-1}]	5.9	9.5	14.0	18.7

The tank water temperature profiles of the four UTBs under the two conditions were plotted in figures 13 and 14, respectively.

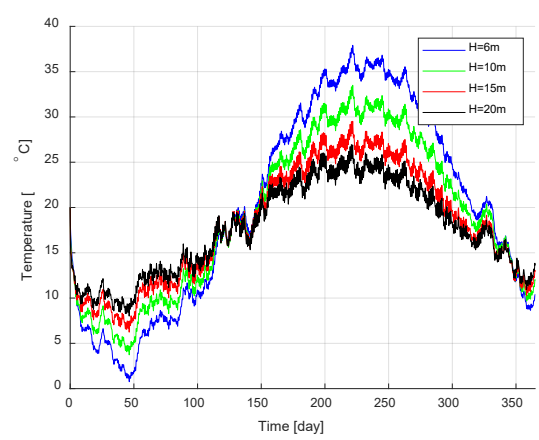

Figure 13. Tank water temperature profiles of four UTBs with identical heat transfer area under the variable soil temperature condition

The results show that, with the same heat transfer area, the longer UTB has less temperature fluctuation, which will result in higher efficiency of the GSHP. Similar to the previous parametric study, it is because the longer

UTB exposes to deeper soil, and the corresponding higher surface-to-volume ratio helps increase the heat exchange rate between the UTB and the surrounding soil. The much lower fluctuation indicates that if UTBs with a longer length are used, the total number of UTBs to meet the thermal loads can be reduced.

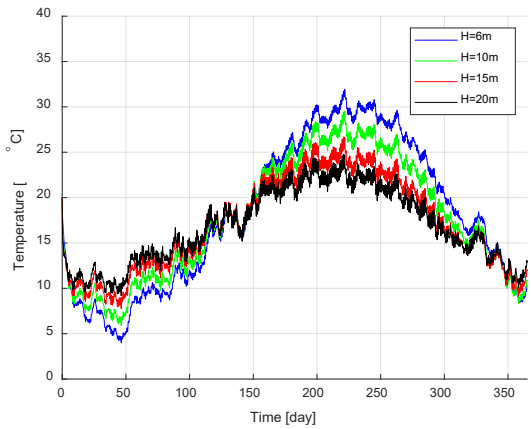

Figure 14. Tank water temperature profiles of four UTBs with identical heat transfer area under the uniform soil temperature condition

The RMSD and the annual maximum tank temperature trends for the four UTBs are similar to the previous parametric study, thus it is not repeated here.

CONCLUSION

This study investigated the impact of seasonal soil temperature variation along with the depth of soil on the simulation results of the UTB. A validated 2D model was used to predict the UTB's annual performance under different conditions. The main conclusions drawn from this study include:

- The seasonal soil temperature variation has an impact on the tank temperature of the UTB. The assumption of a uniform and constant soil temperature will result in an RMSD of 3.6 ºC in predicted tank temperature and thus lead to a 6% underestimation of the annual power consumption of the GSHP system. While this error is noticeable, they are not very significant.
- The dimensions of the UTB play an important role in its performance. With the same volume or same heat transfer area, a longer UTB has significantly less temperature fluctuation, leading to higher efficiency of the GSHP system. However, a longer UTB needs to be installed in a deeper borehole, which will increase the drilling cost. Therefore, a trade-off between the cost and performance is needed to maximize the cost-effectiveness of the UTB.

REFERENCES

Bertermann, D., Bernardi, A., Pockelé, L., Galgaro, A., Cultrera, M., de Carli, M., & Müller, J. 2018. European project "Cheap-GSHPs": installation and monitoring of newly designed helicoidal ground source heat exchanger on the German test site. Environmental earth sciences, 77(5), 180.

Bose, J. E. (1985). Design/data manual for closed-loop ground-coupled heat pump systems. ASHRAE.

CDH Energy Corp. (Frontier Energy). 2017. Final Report for Analysis of Water Furnace Geothermal Heat Pump Sites in New York State with Symphony Monitoring System. Submitted to New York State Energy Research and Development Authority.

Fridleifsson, I. B., Bertani, R., Huenges, E., Lund, J. W., Ragnarsson, A., & Rybach, L. 2008. The possible role and contribution of geothermal energy to the mitigation of climate change. In IPCC scoping meeting on renewable energy sources, proceedings, Luebeck, Germany.

Im, P., Hughes, P., & Liu, X. 2012. Demonstration and Performance Monitoring of Foundation Heat Exchangers (FHX) in Ultra-High Energy Efficient Research Homes. Proceedings of the 17th ACEEE Summer Study on Energy Efficiency in Buildings. August, Pacific Grove, CA.

Warner, J., Liu, X., Shi, L., Qu, M., & Zhang, M. (2020). A novel shallow bore ground heat exchanger for ground source heat pump applications—Model development and validation. Applied Thermal Engineering, 164, 114460.

Liu, X., McCabe, K., Hughes, P., Spitler, J., Southard, L., & Warner, J. 2019. GeoVision Analysis Supporting Task Force Report: Thermal Applications—Geothermal Heat Pumps. Oak Ridge National Lab., Oak Ridge, TN.

Liu, X., Polsky, Y., Qian, D., & Mcdonals, J. 2018. Analysis of Cost Reduction Potential of Vertical Bore Ground Heat Exchanger (Final). Oak Ridge National Lab., Oak Ridge, TN.

NYSERDA (New York State Energy Research and Development Authority). 2017. Renewable Heating and Cooling Policy Framework.

Wilcox, S., & Marion, W. 2008. Users manual for TMY3 data sets. Golden, CO: National Renewable Energy Laboratory.

Xing, L., & Spitler, J. D. 2017. Prediction of undisturbed ground temperature using analytical and numerical modeling. Part I: Model development and experimental validation. Science and Technology for the Built Environment, 23(5), 787-808.

Zhang, M., Liu, X., Biswas, K., & Warner, J. 2019. A three-dimensional numerical investigation of a novel shallow bore ground heat exchanger integrated with phase change material. Applied Thermal Engineering, 162, 114297.