Preliminary Investigation of the Effect of Horizontal Piping on the Performance of a Vertical Ground Heat Exchanger System

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ABSTRACT

In a typical ground-source heat pump system utilizing a vertical ground heat exchanger, the horizontal piping connecting boreholes can exceed 10% of the total length of the vertical installation. In designing such systems, the effect of the horizontal piping on the thermal performance of the system is typically neglected; however, there has not been an effort to quantify the effect of this assumption. This work studies two buildings in two locations with a simulated vertical ground heat exchanger, both with and without the addition of a horizontal ground heat exchanger, to determine a first-order approximation of the effect that the horizontal piping has on the performance of the system as a whole. The results show that, using a ten-year simulation period, the inclusion of the horizontal piping in the simulation leads to a mitigation of heat pump entering fluid temperatures of up to 0.8°C (1.4°F). Additionally, the horizontal ground heat exchanger is found to be equivalent to up to 30% of the installed vertical length for the cases studied.

INTRODUCTION

Ground-source heat pump (GSHP) systems are utilized frequently in "sustainable" heating and cooling systems worldwide, with an estimated total heating capacity of 35 GW (118 billion Btu/h) installed across at least 3.0 million units in residential, commercial, and industrial settings (Lund 2011). For any heating or cooling system design, it is important to have an accurate procedure for sizing the equipment so that the system may be adequately sized. A system that is undersized may lead to equipment failure, while an oversized system is often inefficient and excessively expensive. This is particularly critical for sizing vertical ground heat exchangers (VGHXs) used in GSHP systems, where the cost of the ground heat exchanger represents a significant increase in first cost compared to more conventional systems.

Also, unlike conventional systems that are often sized based on a peak cooling load and/or peak heating load, the very long time constant of the ground necessitates accounting for heat transfer to/from the ground over a period of many years. It is possible for maximum heat pump entering fluid temperatures (EFTs) to rise from year to year over the life of the system for buildings that annually reject more heat than they extract. Conversely, buildings that annually extract more heat than they reject have the possibility of minimum heat pump EFT falling from year to year. At least two approaches have been taken to account for this phenomenon. Kavanaugh and Rafferty (1997) describe a simple procedure that uses a table of factors to estimate the long-term change in ground field temperature; the basis of these factors is not provided. The other approach is to use a simulation of the VGHX with ground thermal properties, building loads, heat pump performance characteristics, and ground heat exchanger design as inputs. The simulation predicts the evolution of temperature with time, and the size of the ground heat exchanger is adjusted automatically to meet user-specified minimum and maximum heat pump EFTs. The simulation of vertical ground heat exchangers is discussed in detail in the next section.

Regardless of which approach is used, there are certain approximations that are inherent in the approaches. For the simulation approach, these approximations include pure conduction heat transfer (no groundwater flow or unsaturated moisture transport), uniform ground thermal properties, an upper surface boundary temperature equivalent to the annual average ground temperature, and consideration of heat trans-

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fer to/from the VGHX only—losses or gains from the horizontal distribution piping are neglected. Although the basis of the long-term temperature change factors is not clear, the simplified procedure of Kavanaugh and Rafferty (1997) is believed to be derived using all of the same assumptions.

In recent years, there has been some controversy within the cognizant ASHRAE Technical Committee (TC) 6.8, Geothermal Heat Pump and Energy Recovery Applications, as to whether or not some of these assumptions may lead to the simulation approach overpredicting long-term heat pump EFT rise or fall. In fact, this goes back some years; accompanying the long-term temperature change factor table in the Kavanaugh and Rafferty (1997) reference is this statement: "The values in this table represent worst-case scenarios, and the temperature change will usually be mitigated by groundwater recharge (vertical flow), groundwater movement (horizontal flow) and evaporation (and condensation) of water in the soil." It is certainly the case that each of these phenomena, if present, will mitigate the long-term temperature change to some degree. Chiasson et al. (2000) have numerically investigated the effect of horizontal groundwater flow on both the thermal response tests used to measure ground thermal conductivity and on long-term performance of ground heat exchangers. That work suggests that horizontal groundwater flow is only likely to significantly affect borehole temperatures in sands, gravels, and karst limestones. The other effects have not been quantified in the published literature.

This paper, though, examines one of the other assumptions—namely, neglecting heat transfer to/from the horizontal piping. The effects of this assumption have not, to date, been reported in the literature, despite the fact that horizontal piping can amount to more than 10% of the total installed vertical length. Obviously, this could be expected to have an effect on system behavior. To examine this effect, this work analyzes, as a first approximation, a VGHX and a horizontal ground heat exchanger (HGHX) coupled in series, with no thermal interference (via conduction heat transfer) between them. This will provide an upper-end estimate for the effect of horizontal piping on the performance of a VGHX system.

METHODOLOGY

To determine the effect of horizontal piping on a vertical borehole system, simulations of both a VGHX and a HGHX are needed. Additionally, two different buildings, each placed in two locations, were chosen to get an idea of the influence of horizontal piping when considering system size and dominant mode of operation of the system.

Simulation of Vertical Ground Heat Exchangers

Numerical simulations of vertical boreholes have been performed since the work of Eskilson (1987), who computed response functions ("g-functions") for specific borefield geometries based on superposition of a two-dimensional, radial-axial simulation of a single borehole. This approach has been improved to account for behavior at short time steps (Yavuzturk and Spitler 1999) and a variable convective resistance inside the pipe (Xu and Spitler 2006). The general g-function method has since been utilized in a number of design tools (Hellström and Sanner 2000; Spitler 2000) as well as more general energy simulation tools such as EnergyPlus (Fisher et al. 2006) and eQUEST (Liu 2008). These tools can predict the average fluid temperature in the heat exchanger as well as at the inlet and exit (i.e., the heat pump outlet and inlet). Key assumptions in this method include consideration of conduction as the sole method of heat transfer, no header piping, and no direct consideration of moisture transfer in the soil (Eskilson 1987), although Kavanaugh and Rafferty (1997) propose shortening the sizing period in their equation-based design method when moisture transfer may become a factor.

The g-function model, as implemented in a design tool, has been validated by Cullin (2008) for a three-borehole system. Eighteen months of experimental data from a hybrid ground-source heat pump test facility in Stillwater, Oklahoma, were used in the validation; using measured heat extraction/rejection rates, the predicted heat pump end-of-month EFTs were typically within 1°C (1.8°F) of the experimental values. Several sources of error were analyzed, including a mismatch between experimental operation and the constant behavior typically assumed in a simulation. In addition, for simulations using a monthly time step and monthly total/monthly peak load profiles, a single peak duration may not be appropriate for any given simulation. Shoulder seasons may also introduce some error as heat pumps switch between heating and cooling modes within a single month. Nevertheless, predictions of annual maximum and minimum heat pump EFTs were within 3°C (5°F) despite these issues, with the larger differences due to these reasons.

Other VGHX simulation techniques do not use the g-function approach. Hellström (1989) developed a "duct ground heat storage" model that superimposes numerically computed transient heat transfer solutions between the storage volume and far-field, as well as around the boreholes on a short time scale, with the analytically determined steady-flux heat transfer solution around the nearest pipe. Another simulation software combines a cylinder source model around a single borehole (Bernier et al. 2004) with thermal response factors generated with a finite line source method (Sheriff and Bernier 2008). Cui et al. (2007) created a VGHX simulation coupling an analytical finite line source solution outside the borehole with a quasi-three-dimensional model inside the borehole to determine the temperature of each individual borehole.

For this work, the g-function approach as enhanced by Xu and Spitler (2006) is used. This model was selected for its computational accuracy, as the design tool (Spitler 2000) in which it is implemented has been validated against experimental data (Cullin 2008) as discussed previously. The EnergyPlus model (Fisher et al. 2006) utilizes g-functions that can be generated by this design tool and has itself been verified as part of general EnergyPlus development (DOE 2012).

Simulation of Horizontal Ground Heat Exchangers

Horizontal heat exchangers have been modeled with limited flexibility by Mei (1988) and Piechowski (1999). Mei (1988) utilized a radial coordinate system surrounding either one or two pipes in the domain to calculate the temperature response of the heat exchanger. The approach relies on a far-field boundary condition imposed at the radial coordinate system boundary, without a detailed surface heat balance. Piechowski (1999) utilized a dual coordinate system approach to create an efficient numerical mesh. A Cartesian mesh is employed in a three-dimensional soil region with specific cells containing a radial mesh within. The radial system consists of, from outside in, a series of soil cells, then the pipe cross section, and finally the fluid cross section. This methodology requires an interface between the two coordinate systems but results in an efficient approach to localize computational effort in the near-pipe region, where thermal activity is expected to be highest.

A new finite-volume numerical model for horizontal ground heat exchangers based on this dual coordinate system was developed by Xing et al. (2011) and also described by Hughes and Im (2012). One of the enhancements to the original approach is the ability to include any number of pipes in the domain and using a flow-wise solution algorithm to simulate entire piping circuits within the domain. In this way, since each pipe is represented by an individual radial coordinate region within the larger Cartesian domain, interaction between pipes is considered. Additional boundary conditions were implemented to allow the ground model to tightly integrate with the zone heat balance algorithms in the building simulation program EnergyPlus (DOE 2012). The surface heat balance was modified to include all essential heat transfer mechanisms, including convection to the outdoor air, conduction to the soil, environmental radiation (both long- and short-wave), and evapotranspiration. The evapotranspiration model is based on the standardized equation developed by Walter et al. (2005). In addition, freezing in the soil, both at the ground surface and, potentially, around the heat exchanger piping, is considered. The undisturbed ground temperature at any particular depth is set with the Kusuda and Achenbach (1965) model, which uses an exponentially decaying sinusoid to estimate the seasonal penetration of heat from the surface; this model is used to update the far-field boundary at each time step.

The HGHX model was validated analytically (Hughes and Im 2012) using idealized boundary conditions and constant thermal properties to evaluate the model using a line source technique. The numerical model agreed with a high degree of accuracy to this analytic solution. The model was then validated experimentally using data from a foundation heat exchanger test site near Oak Ridge, Tennessee; a foundation heat exchanger is simply an HGHX installed near a basement wall, typically laid in the excavated foundation during building construction. For the HGHX model, another boundary condition was added to account for the presence of the basement. The model predicted system temperatures with an annual mean bias error of 1.3°C (2.3°F) and predicted basement wall heat flux with an annual mean bias error of 1.1 W/m^2 (0.35 Btu/h·ft^2).

Locations, Buildings, and Soil

Two buildings and two locations were chosen for a small-scale study. One building is a house, while the other is an office building; these particular buildings were chosen because they provide reasonable loads for both a small residential-scale borefield as well as a rather large commercial-scale borefield.

Locations. Two locations—Duluth, Minnesota, and Tulsa, Oklahoma—were selected to provide both a warm and a cool locale. The locations are specified in the simulations by means of Typical Meteorological Year (TMY) weather files. Loads for each combination of building and location were generated with EnergyPlus (Crawley et al. 2001); this was done separately from the ground heat exchanger simulation, as only the temperature response of the ground is of interest at this time. Load profiles are shown in Figures 1–4. The Duluth house (Figure 1) is moderately heating dominated, with a heating-to-cooling ratio of 1.47; while the Tulsa house (Figure 2) is cooling dominated, with a ratio of 0.28. The Duluth office building (Figure 3), however, is relatively balanced, with a

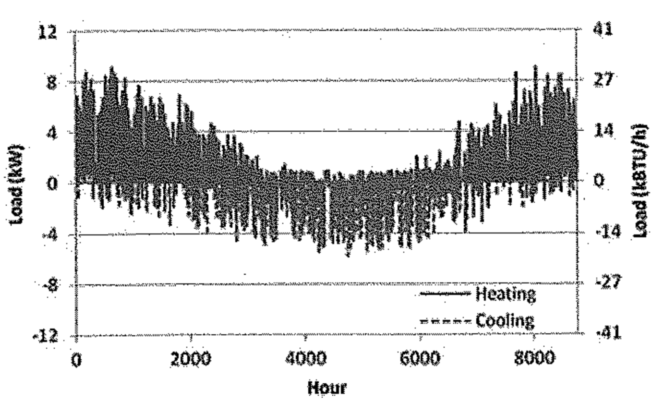

Figure 1 Load profile for Duluth house.

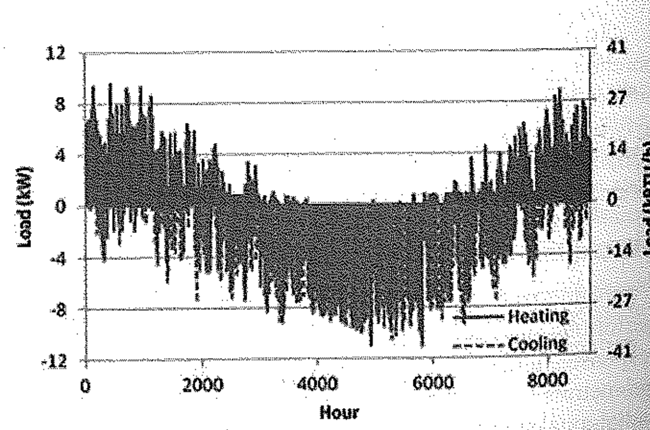

Figure 2 Load profile for Tulsa house.

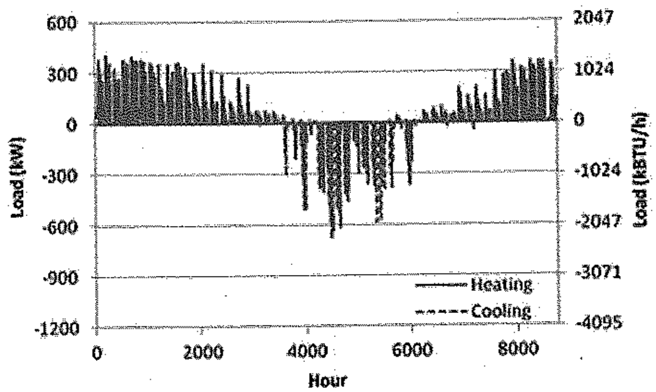

Figure 3 Load profile for Duluth office building.

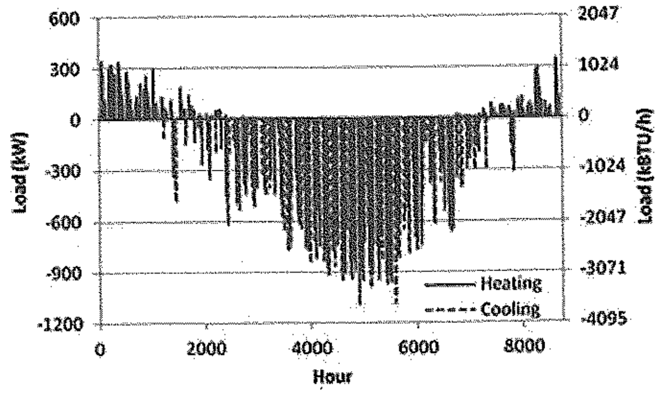

Figure 4 Load profile for Tulsa office building.

heating-to-cooling ratio of 1.04; while the Tulsa office building (Figure 4) is substantially cooling dominated with a ratio of 0.033. It should be noted that while these buildings were operated with a thermostatic control for the purposes of these simulations, in reality (particularly for Duluth) free cooling using outdoor air would be utilized instead of the heat pump system.

House. The house used in this study is a single-family, 100 m^2 (1076 ft^2) dwelling, modeled in EnergyPlus (Crawley et al. 2001). Glazing covers approximately 40% of the north and south walls and 20% of the east and west walls. The house operates on constant thermostatic setpoints of 21°C (70°F) in heating and 24°C (75°F) in cooling, with a deadband between.

Office. The office building used in this study is a three-story office building, 48.8 m (160 ft) in each of the plan dimensions and 9.1 m (30 ft) tall; this building, modeled by Gentry (2007), is a scaled-down version of a real, much taller building located in Tulsa, Oklahoma. Glazing occupies 65% of the building façade, and the building operates with a 0.5 ach infiltration rate. The thermostat is set at 20°C (68°F) for heating and 24°C (75°F) for cooling from 7:00 a.m. to 6:00 p.m. Monday through Friday, with a night and weekend setback of 5°C (41°F) in heating and 30°C (86°F) in cooling, again with a deadband between in both instances.

Soil. For this work, a soil typical of a heavier, damp earth was selected. The soil has a thermal conductivity of 1.30 W/m·K (0.75 Btu/h·ft·°F) and a volumetric heat capacity of 2019 kJ/m^3·K (30.1 Btu/ft^3·°F). For Duluth, the undisturbed ground temperature is 5.0°C (41°F), while for Tulsa it is 16.7°C (62°F).

Component Sizing

VGHXs. For this work, the vertical ground heat exchanger for each combination of building and location was sized using the software developed by Spitler (2000), which utilizes the same g-function approach as EnergyPlus. The individual borehole depth was set to 91.4 m (300 ft); the number of boreholes was adjusted so that the heat pump EFT would be maintained between design constraints of approximately 1°C and 30°C (34°F and 86°F), with a 20% propylene glycol solution specified as the working fluid. Since the working fluid is an antifreeze mixture instead of pure water, the minimum design constraint is somewhat lower than would be used for a pure water system.

For the two Duluth buildings, the design is constrained by the minimum allowable EFT, while the higher temperature constrains the two Tulsa buildings. So, if the Duluth buildings are undersized, that means that the simulated minimum EFT is lower than the constraint; if they are oversized, then the simulated minimum EFT is greater than the constraint. Similarly for the Tulsa buildings, they would be undersized with a simulated maximum EFT higher than the constraint and oversized with a simulated maximum EFT lower than the constraint.

HGHXs. The horizontal piping in a vertical ground heat exchanger system consists of several parts: piping running between boreholes, piping to connect each borehole to the main fluid distribution pipe, and pipe to run from the borefield to the heat pump. Since, for the purposes of this work, the HGHX and VGHX are assumed not to interact with one another (i.e., their respective soil domains are isolated from one another and there is no conductive heat transfer between them), only one piping configuration was selected, with two pipes in the horizontal trench. The VGHX is piped in reverse-return configuration, and a simple equation for the total horizontal length was developed based on the borehole configuration and spacing for a rectangular borefield.

A typical borefield is shown in Figure 5. For a borefield containing X-by-Y boreholes ($X \geq Y$) spaced s meters apart, there will be sX meters of horizontal piping in one run of boreholes and Y such runs. Additionally, there will be $s(Y - 1)$ meters of header piping connecting each of the parallel runs. For this work, a spacing of $s = 5.0$ m (16.4 ft) is used. To join each borehole to the main piping lines, there will be a short connecting pipe of length a; in this work, a is given a value of 0.20 m (0.66 ft). Finally, for a reverse-return piping scheme, this will be done once for supply and once for return, leading to Equation 1, which gives the total horizontal length, THL, for an arbitrary borefield configuration assuming that the distance to the building is very short.

$$THL = 2[sXY + s(Y-1) + aXY] \quad (1)$$

Table 1 shows the sizes of both the vertical and horizontal components for each combination of building and location. The horizontal length listed in the table includes only one pipe of the reverse-return configuration. Table 1 also shows two different ratios relating the horizontal and vertical installations. The horizontal to vertica (H/V) piping ratio is the ratio of the actual length of piping used; so, for a vertical borehole, it will be twice the design length, as a U-tube has both downward and upward segments. The H/V length ratio, then, is simply the ratio of design lengths (horizontal trench length to total bore length) and is twice the piping ratio. Finally, to mirror the physical borefield using a reverse-return configuration, the simulated HGHX consists of two pipes, spaced 0.5 m (1.6 ft) apart.

RESULTS

Base Cases

For each of the two buildings in both locations, simulations were run in the EnergyPlus environment both with and without a HGHX. For the systems that include the HGHX, the horizontal piping is buried 3 m (10 ft) below the ground surface; while this is deeper than the horizontal piping would be practically installed, this depth was chosen to isolate the additional heat transfer to the ground from the horizontal piping from the heat transfer through the surface to outside conditions. Additionally, a 1 m (3.3 ft) deep HGHX was investigated, as this depth range should bracket the depths for which horizontal distribution piping would be installed and therefore also bracket the net effect of the piping on the thermal performance of the system. Figure 6 shows the minimum monthly heat pump EFT (for Duluth buildings) and maximum monthly heat pump EFT (for Tulsa buildings) for the simulation containing both the VGHX and HGHX. The two Tulsa buildings, in particular, show evidence of heat buildup over time, while the heat pump EFT for the Duluth buildings remains consistent on a yearly basis. The plots in Figures 7–10 show the deviation from these values for a system that does not consider the system's horizontal piping.

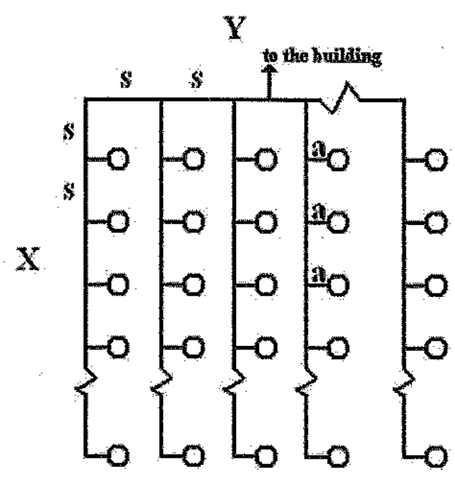

Figure 5 *Borefield piping diagram.*

For a heating-constrained system in Duluth, Minnesota, Figures 7 and 8 show the difference in heat pump EFT between a system with just a VGHX and a system with a HGHX in addition to a VGHX. For the house in Duluth (Figure 7), the five-borehole, heating-dominated system shows very little deviation in temperature due to the presence of the HGHX; overall, the effect averages about 0.05°C (0.09°F), and there is no appreciable increase or decrease over the course of ten years. For the office in Duluth (Figure 8), however, there is an obvious downward trend, which indicates that the system with the HGHX is predicting a higher temperature than the system with the VGHX alone. In ten years, the peak difference is about 0.5°C (0.9°F); while this could represent an opportunity to slightly reduce the size of the initial VGHX since the HGHX is supplying more heat to the system, it is important to note that this estimate is on the high end, as there is no calculated interaction between the two heat exchangers. Nevertheless, the question of whether it might be possible to take advantage of

Table 1. Heat Exchanger Sizes

Building, Location	Vertical Configuration	Borehole Depth, m (ft)	Total Vertical Length, m (ft)	Horizontal Length, m (ft)	H/V Piping Ratio, %	H/V Length Ratio, %
House, Duluth	1×5	91.44 (300)	457 (1500)	52 (171)	5.7%	11.4%
House, Tulsa	1×3	91.44 (300)	274 (900)	32 (105)	5.8%	11.7%
Office, Duluth	13×16	91.44 (300)	19,020 (62,400)	2314 (7592)	6.1%	12.2%
Office, Tulsa	20×22	91.44 (300)	40,234 (132,000)	4766 (15,636)	5.9%	11.8%

the horizontal piping by intentionally undersizing the VGHX is addressed in the next section:

Figures 9 and 10 show the same difference in heat pump EFT for a house and an office building, respectively, in the cooling-dominated climate of Tulsa, Oklahoma. For the Tulsa house (Figure 9), the temperature difference is positive, indicating that the HGHX is acting as an additional heat sink. Even for a VGHX with just three boreholes, the peak effect is about 0.6°C (1.1°F) after ten years. This is a much more pronounced effect than for the similarly sized heating-dominated system in Duluth. Peak fluid temperatures in the Tulsa house system are around 30°C (86°F) while the undisturbed ground temperature is 17°C (62°F); for the Duluth house system, however, the peak temperature is about 1°C (34°F) with an undisturbed ground temperature of only 5°C (41°F). Thus, in Tulsa there is a much greater temperature range available for heat transfer in the soil and consequently higher secondary heat transfer from the horizontal piping.

For the Tulsa office building (Figure 10), the influence of horizontal piping is pronounced. Over the course of a ten-year simulation, the system with the HGHX has a peak maximum heat pump EFT 0.8°C (1.4°F) lower than the base system with the VGHX alone. Additionally, after the first few years, the difference is growing on the order of 0.1°C (0.2°F) per year and shows no indication of dampening after ten years. This indicates that, at least for a relatively large cooling-dominated ground heat exchanger system, it may be possible to intention-

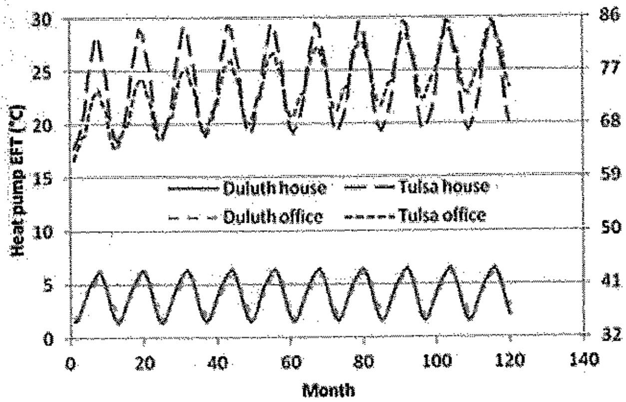

Figure 6 *Base case maximum (for Tulsa) and minimum (for Duluth) monthly heat pump EFTs.*

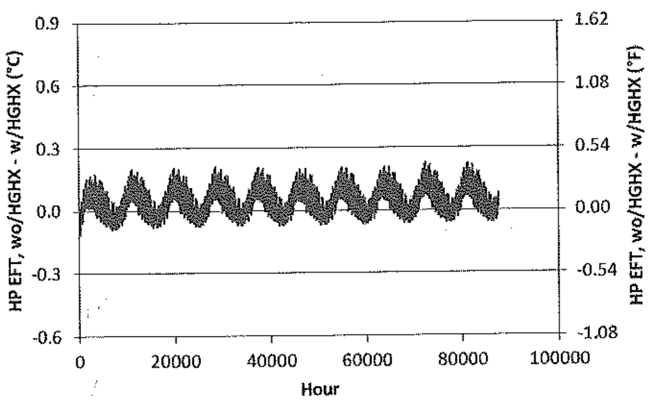

Figure 7 *Effect of horizontal piping on a house in Duluth.*

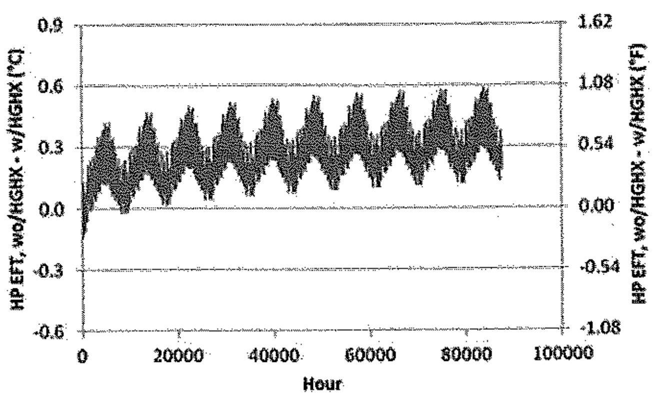

Figure 9 *Effect of horizontal piping on a house in Tulsa.*

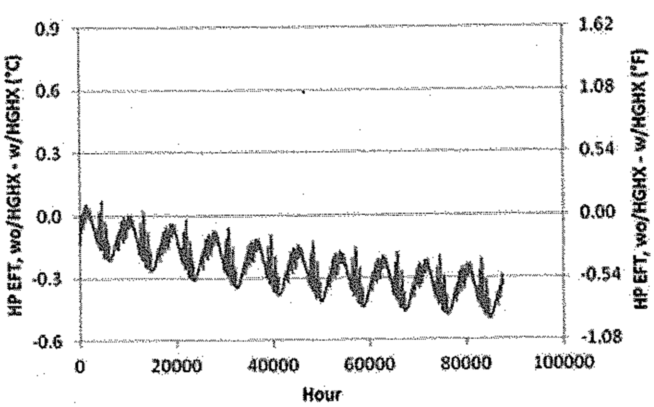

Figure 8 *Effect of horizontal piping on an office building in Duluth.*

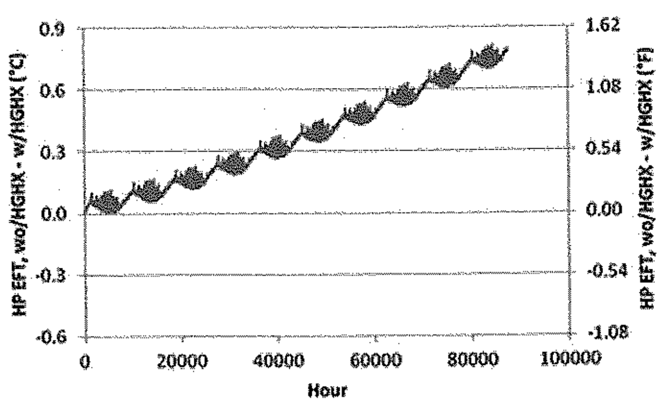

Figure 10 *Effect of horizontal piping on an office building in Tulsa.*

ally undersize the VGHX—at least based on current sizing techniques—and still meet the desired design constraints.

Changing the Length of the VGHX

As the vertical ground heat exchanger becomes more undersized by reducing its depth, the horizontal piping becomes a greater fraction of the total length of heat exchanger in the soil. Thus, it would be expected to have a greater influence on the behavior of the system as a whole. In addition, the results from a system sized through current simulation techniques suggest that, at least for a VGHX in a larger, cooling-dominated system, the presence of horizontal piping could make up for a slight undersizing (a few percent, perhaps) of the vertical boreholes. For the houses and office buildings in both Duluth and Tulsa, Table 2 shows the maximum difference in heat pump EFT when the VGHX is undersized between a system without a HGHX and one in which the HGHX is considered. Since the HGHX length remains constant, this undersizing increases the ratio of horizontal to vertical design length from about 12% for a fully sized VGHX to around 18% when the VGHX is reduced to 70% of the base size.

As Table 2 indicates, as the size of the VGHX decreases, the total effect of the horizontal piping increases. This is as anticipated, since there is now comparatively more horizontal piping for heat to transfer through. The effect is greater for the cooling-dominated buildings in Tulsa than the heating-dominated buildings in Duluth since, again, there is a larger difference between the fluid temperature in the loop and the ground temperature, on average. The horizontal piping produces the most significant effect for the Tulsa office building, as there is an 0.81°C (1.47°F) difference between the two systems with a normally sized VGHX and a 1.48°C (2.67°F) difference when the VGHX is reduced to 70% of its base size.

A similar effect may be seen when the heat exchanger is oversized. Table 3 shows the effect of the horizontal piping on system performance when the VGHX depth is increased up to 130% of its base size. As the size of the VGHX increases, the fraction of total pipe length accounted for by the HGHX decreases; thus, as expected, the difference between the two systems drops, as the horizontal piping has less of an impact.

Effect of HGHX Depth

While the horizontal piping effect shown so far indicates a practically significant, if not statistically significant, effect, the horizontal pipe for a VGHX is typically buried much closer to the surface than the 3 m (10 ft) considered thus far. So, to explore the effect of the depth of the horizontal piping, the simulations were repeated with the HGHX moved up to 1 m (3.3 ft) below the surface, which would be closer to how it might be installed in an actual system. At this depth, the HGHX might also be expected to interact much more with outdoor weather conditions.

Table 4 shows the results of the same undersizing study, this time with the horizontal piping buried much closer to the surface. In each instance, the maximum temperature difference increases with the horizontal pipe closer to the surface. At just 1 m (3.3 ft) below ground, the piping has a much greater ability to interact with the top layers of the soil. In cold months, the fluid temperature will be around 1°C (34°F), while the average outdoor air temperature is higher than that; as a result,

Table 2. Effect of Horizontal Piping at 3 m (10 ft) when VGHX is Undersized

Building, Location	Maximum Difference in Heat Pump EFT: w/o HGHX – w/HGHX, °C (°F)			
	100% VGHX Size	90% VGHX Size	80% VGHX Size	70% VGHX Size
House, Duluth	–0.11 (–0.20)	–0.12 (–0.23)	–0.18 (–0.32)	–0.21 (–0.38)
House, Tulsa	0.58 (1.06)	0.63 (1.13)	0.75 (1.35)	0.95 (1.70)
Office, Duluth	–0.50 (–0.90)	–0.54 (–0.97)	–0.58 (–1.05)	–0.63 (–1.13)
Office, Tulsa	0.81 (1.47)	1.12 (1.83)	1.26 (2.27)	1.48 (2.67)

Table 3. Effect of Horizontal Piping at 3 m (10 ft) when VGHX is Oversized

Building, Location	Maximum Difference in Heat Pump EFT: w/o HGHX – w/HGHX, °C (°F)			
	100% VGHX Size	110% VGHX Size	120% VGHX Size	130% VGHX Size
House, Duluth	–0.11 (–0.20)	–0.10 (–0.18)	–0.08 (–0.15)	–0.08 (–0.14)
House, Tulsa	0.58 (1.06)	0.51 (0.91)	0.44 (0.80)	0.40 (0.71)
Office, Duluth	–0.50 (–0.90)	–0.13 (–0.24)	–0.13 (0.23)	–0.12 (–0.22)
Office, Tulsa	0.81 (1.47)	0.65 (1.17)	0.61 (1.10)	0.56 (1.01)

Table 4. Effect of Horizontal Piping at 1 m (3.3 ft) when VGHX is Undersized

Building, Location	Maximum Difference in Heat Pump EFT: w/o HGHX – w/HGHX, °C (°F)			
	100% VGHX Size	90% VGHX Size	80% VGHX Size	70% VGHX Size
House, Duluth	–0.36 (–0.65)	–0.38 (–0.68)	–0.41 (–0.74)	–0.43 (–0.77)
House, Tulsa	0.73 (1.31)	0.77 (1.39)	0.87 (1.56)	1.02 (1.84)
Office, Duluth	–0.60 (–1.08)	–0.63 (–1.13)	–0.65 (–1.17)	–0.71 (–1.29)
Office, Tulsa	1.14 (2.05)	1.39 (2.50)	1.68 (3.03)	2.01 (3.62)

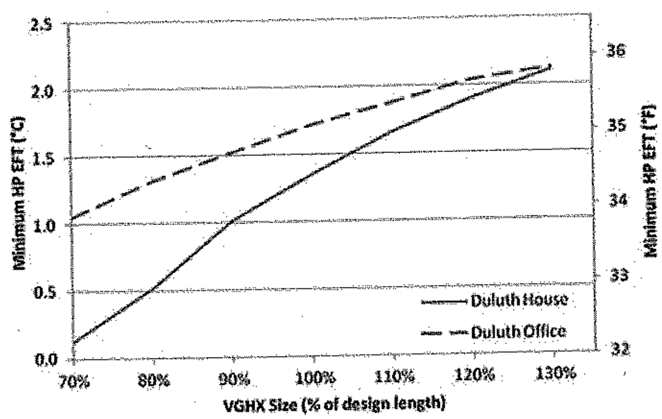

Figure 11 Minimum heat pump EFT vs. design length for Duluth buildings.

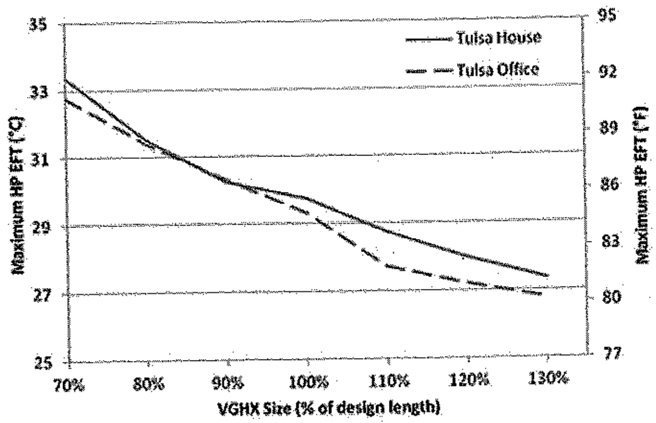

Figure 12 Maximum heat pump EFT vs. design length for Tulsa buildings.

the top layers of soil will be warmed by convection and radiation and the horizontal piping can absorb this heat. In contrast, during hot months, the temperature in the loop will be closer to 30°C (86°F) and heat will be transferred from ground to air by means of convection and evapotranspiration, so the horizontal piping can reject extra heat and lower the temperature in the ground loop.

Sensitivity in Design Length

The horizontal piping in a VGHX system has a noticeable effect on the temperatures entering the heat pump, as the HGHX can reject extra heat in summer and absorb it in cooler months. What, then, is the impact of this on design length? Can the horizontal piping be expressed in terms of an equivalent amount of vertical U-tube, assuming no HGHX influence? To explore this, a sensitivity analysis was performed to determine the influence of the horizontal piping on design length, as the VGHX is both undersized *and* oversized. Using a sensitivity coefficient approach (Spitler et al. 1989), the error in design length due to the error in heat pump EFT caused by neglecting the influence of the horizontal piping may be estimated as follows:

$$E_{length} \approx \frac{\partial L}{dEFT} \cdot E_{EFT} \approx \frac{\Delta L}{\Delta EFT} \cdot E_{EFT} \tag{2}$$

The partial derivative here is estimated from the change in design length and maximum (for cooling) or minimum (for heating) heat pump EFTs. For the Duluth house with the 3 m (10 ft) HGHX, the partial derivative is 31.2% per degree, so an error of 0.11°C (0.19°F) in the EFT would lead to an error in the design length of approximately 3.4%. Similarly, errors for the Tulsa house, Duluth office, and Tulsa office, respectively, are 7.8%, 28.1%, and 6.2%.

Another way to explore how the horizontal piping affects the design length is to express the horizontal length as an equivalent length of vertical piping. Results so far have shown that considering the HGHX leads to a system that over-performs; i.e., the design limits are not reached because the HGHX compensates for additional heat extraction or rejection. For each system, curves can be generated that show the trend in maximum or minimum heat pump EFT when the VGHX design length changes. From these curves, the HGHX equivalent vertical length may be obtained by tracking back on this curve from the design point to the point at which the heat pump temperature constraint is identically met; the difference in lengths is due to the consideration of active horizontal piping and represents the length of VGHX that the horizontal piping is equivalent to. Figure 11 shows the EFT versus design length curves for the Duluth buildings, while Figure 12 shows the same for the Tulsa buildings. The 100% design lengths are the same used previously, targeted to 1°C (34°F) for heating and 30°C (86°F) for cooling. Taking the Duluth house as an example, the minimum heat pump EFT using the design length is 1.35°C (34.4°F); following this curve back finds the 1°C (34°F) constraint at about 89% of the design length. Thus, for this system, the horizontal piping could be said to be equivalent to 11% of the total vertical length. Similarly, the equivalent vertical length of horizontal piping is around 9% of the total vertical length for the two Tulsa buildings, while it accounts for roughly 30% for the Duluth office. More study is definitely needed to examine the interactions between the horizontal and vertical components; since the interactions between horizontal and vertical piping were neglected, these values are only estimates and are likely on the high end.

One important thing to note about Figures 11 and 12 is the effect of design temperature limits on the resulting heat exchanger size. If the design constraint is increased for cooling or decreased for heating, the required VGHX length will drop—sometimes significantly, as for the Duluth house—even for only a degree's change in the constraint. If a system is sized using less extreme limits, then the heat exchanger could end up being quite a bit oversized, particularly if the heat pump and other equipment are capable of handling those more extreme temperatures. In other words, the amount by which a system is oversized or undersized depends not only on the temperature response but also on the EFT constraints placed upon the design. In addition to being economically inefficient, this could certainly provide one explanation as to why some real systems do not exhibit the long-term temperature change frequently foreseen in simulation.

CONCLUSIONS

This work represents an initial exploration of the effect of horizontal piping on the performance of ground-source heat pump systems that utilize vertical ground heat exchangers. In simulating two buildings in two different locations, a horizontal ground heat exchanger was added in series with a vertical ground heat exchanger, and the results were compared with a system consisting of the VGHX alone. Results for the base case, with the HGHX located 3 m (10 ft) below the ground surface, showed that the HGHX plays a role in the temperature response of the entire system, rejecting extra heat in summer months in the warmer location while extracting extra heat during winter months in the cooler location. When the horizontal piping is moved closer to the surface, the effect is amplified.

As the depth of the VGHX shrinks, the horizontal piping becomes a greater proportion of the total pipe length of the system. As would be expected, the difference between a simulation with the HGHX and one without grows as the VGHX is undersized and decreases as it is oversized. Additionally, both a sensitivity analysis and an estimation of the equivalent length of VGHX for the horizontal piping were performed. The office in Duluth showed the highest sensitivity and influence of the horizontal piping, with the horizontal piping being equivalent to about 30% of the VGHX design depth. While no exploration of statistical significance was performed, it is more important to note that these results are *practically* significant, in that a designing engineer may want to consider the presence of horizontal piping when designing a system with a VGHX.

This study has assumed no conductive interaction between the horizontal and vertical piping, while in reality there will be some interplay between the two. This should certainly be explored in future work. In addition, these results strongly suggest that the design temperature constraints play a very important role in the expected behavior of a ground heat exchanger system. A system designed with higher extreme temperatures will result in smaller design lengths, though this may result in a long-term change in ground temperatures if the design length is sufficiently low.

These effects have not yet been experimentally quantified. While it would, in theory, be possible to add temperature sensors at the inlet and outlet of each borehole, it would be quite expensive to instrument, maintain, and monitor such a system and we do not anticipate this happening in the near future. Rather, this study suggests one partial explanation for why VGHX design tools (that assume pure conduction heat transfer to/from the VGHX only) are thought to overpredict long-term temperature rise or fall.

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