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Ground heat exchangers with large diameter pipes: What are the benefits?

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ABSTRACT

The geothermal industry has recently been opting for large high-density polyethylene pipes to design vertical ground heat exchangers of ground-coupled heat pump system. Thus, we hypothesized that large diameter pipes can help improve heat exchange rate with the subsurface and made this study with the objective of quantifying the benefits gained with U-loop configurations. The finite line source equation and the multipole model were used to evaluate the maximum heat exchange rate that can be achieved with increasing pipe diameter. Sizing calculations were then performed for a school building in Boston. Ground heat exchangers with a single U-pipe having a nominal diameter of 1.25, 1.5 and 2 inches, as well as a double U-pipe, having a nominal diameter of 1.5 inches, were considered. Results highlighted that the double loop is by far the most efficient configuration, followed by the single loop with a 2 inches pipe diameter, respectively providing heat exchange rates that were 16% and 6% greater and total borehole length that were 22 and 9% smaller when compared to single loop with a 1.25 inches diameter. The use of large diameter pipes was shown without a doubt to benefit ground heat exchanger performances.

INTRODUCTION

Designing ground-coupled heat pump (GCHP) systems requires to minimize the borehole thermal resistance of closed-loop ground heat exchangers (GHE) to maximize heat transfer with the subsurface and ultimately decrease the total borehole length required to fulfill the building energy requirements. Boreholes are an expensive component of GCHP systems (Hénault et al., 2016; Robert and Gosselin, 2014), which can be made financially attractive by increasing the thermal performances of GHE. Various options are available to increase the performance of GHE, which commonly includes (1) adjusting the borehole diameter (Luo et al., 2013), (2) increasing the thermal conductivity (TC) of the grout mixture (Desmedt et al., 2012; Lee et al., 2012, 2011) and (3) selecting proper pipe configuration and material (Raymond et al., 2015). Besides, previous research specifically has been done to increase the TC of pipes by mixing high-density polyethylene (HDPE) with additives such as carbon-based nanoparticles (Gosselin et al., 2017). Moreover, coaxial pipe configurations have been extensively studied as it showed elevated GHE performances due to its large surface area and volume of water (Acuña et al., 2011; Acuña and Palm, 2013; Holmberg et al., 2016; Tago et al., 2005; Zanchini et al., 2010). GHE with a double U-pipe was additionally shown to outperform single U-pipe GHE (Florides et al., 2013; Sivasakthivel et al., 2017). Although significant developments in GHE design occurred over the last decade, improvements have not always readily been implemented in the field by practitioners who are dealing with complex installation procedures and requirements. However, one tendency that has been observed in the geothermal heat pump industry is to design GHE with large diameter pipes. For example, the sales of geothermal pipes at Versaprofiles having a 1.5 inches diameter have doubled from 2020 to 2021 and 2 inches diameter pipes have recently become available. This illustrates market-driven changes but what are the benefits of this practice?

Discussing with practitioners looking for innovations that do not add excessive installation complexity, we hypothesized that increasing the pipe diameter can improve thermal performances of GHE. Thus, this study was made with the objective of comparing the performance of different GHE configurations having regular and large diameter pipes. Our scientific hypothesis was verified with computations made in two methodological steps. Initially, maximal heat extraction (heating) and injection (cooling) rates were analytically calculated for GHE configurations with different pipe diameters. Then, sizing calculations for a typical high school building located in a climate corresponding to that of

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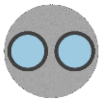
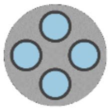
Boston, USA, were made considering the same GHE configurations. In each part of this study, calculations were carried out to highlight the effect of the GHE pipe diameter.

MATERIALS AND METHOD

The study allowed to evaluate the performance of single U-pipe GHE made of HDPE and having a nominal pipe diameter of 1.25, 1.5 and 2 inches, as well as a double U-pipe GHE made of HDPE and having a nominal pipe diameter of 1.5 inches. A surface dimension ratio (SDR) of 11 was considered for all pipe cases. The dimensions of the pipes for each configuration were determined according to the D3035-14a standard (ASTM, 2014). Thus, four different GHE configurations were compared in this study (Table 1). Characteristics of the GHE other than the size and configuration of the pipes were chosen to represent common field conditions. The distance between the center of the pipes (shank spacing) represents an intermediate case between pipes pressed against the wall of the borehole (with clips) and pipes stuck together. The diameter of each borehole was defined based on discussions with practitioners to make sure the pipes can be easily installed into the boreholes. The pipe TC was assumed to be 0.4 W/m/°C for all configurations, which is characteristic of HDPE, and the borehole was assumed to be filled with a thermally enhanced grout having a TC of 1.70 W/m/°C. The heat carrier fluid was assumed to be composed of a mixture of water and propylene glycol with a concentration of 30%.

Table 1 – Characteristics of the ground heat exchangers compared in this study.

Feature	Unit	Single loop 1.25	Single loop 1.5	Single loop 2	Double loop 1.5
Scale drawing	-				
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Shank spacing	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
Pipe TC	W/m/°C	0.4	0.4	0.4	0.4
Grout TC	W/m/°C	1.70	1.70	1.70	1.70

The calculations in study were carried out using an analytical solution describing heat transfer between the GHE and the ground:

$$T_{\mathrm{f}} - T_0 = -\frac{q'_{\mathrm{b}}}{k_{\mathrm{g}}} \cdot G(Fo) - q'_{\mathrm{b}} \cdot R^*_{\mathrm{b}} \qquad (1)$$

where T_{f} and T_0 (°C) are the temperature of the heat carrier fluid and the ground at initial condition, respectively, q'_{b} (W/m) is the heat transfer rate per unit length between the borehole and the ground, k_{g} (W/m/°C) is the ground TC, G is the thermal response G-function calculated with the finite line source equation (Lamarche and Beauchamp 2007) expressed as a function of the Fourier number Fo, and R^*_b (°C·m/W) is the effective fluid-to-ground thermal resistance of the borehole calculated with the multipole method (Claesson and Hellström 2011).

In the first part of this study, the maximum heat injection and extraction rate that can be achieved with each of the four configurations were calculated by rearranging equation 1 as:

$$q'_{\mathrm{b}} = -\frac{T_{\mathrm{f}} - T_0}{R^*_{\mathrm{b}} + \frac{G(Fo)}{k_{\mathrm{g}}}} \tag{2}$$

and by using the following heat budget equation for the borehole:

$$q'_{\mathrm{b}} = \frac{\dot{m} \cdot C \cdot (T_{\mathrm{fo}} - T_{\mathrm{fi}})}{L_{\mathrm{b}}} \tag{3}$$

Moreover, the average temperature of the fluid in the borehole (T_f) and the initial temperature of the ground (T_0) were calculated with:

$$T_{\mathrm{f}} = (T_{\mathrm{fo}} + T_{\mathrm{fi}})/2 \tag{4}$$

$$T_0 = q''_{\mathrm{g}} \frac{(0.5L_{\mathrm{b}} - 4)}{k_{\mathrm{g}}} + T_{\mathrm{g4m}} \tag{5}$$

where T_{fo} and T_{fi} (°C) are the temperature of the fluid leaving and entering the GHE, $\dot{m}$ (kg/s) is the mass flow rate of the heat carrier fluid, C (J/kg/°C) is the specific heat of the fluid, L_{b} (m) is the length of the borehole, q''_{g} (W/m^2) is the terrestrial heat flow, and T_{g4m} is the average undisturbed ground temperature at a depth of 4 m below the ground surface.

The calculations were carried out using a volumetric flow rate of 1.07 L/s for all GHE configurations in both heating and cooling mode. This value was selected to ensure turbulent flow in all pipe sizes (Reynold number above 2500). The use of an identical volumetric flow rate was necessary to make the comparison of results meaningful. The entering water temperature in the borehole T_{fi} was set to a value of -0.5°C in heating mode and to a value of 27.5°C in cooling mode. A mean ground temperature at a depth of 4 m equal 10.5°C was used, which is characteristic for the city of Boston, USA (Wilcox and Marion 2008), and a terrestrial heat flow of 0.064 W/m^2 was considered to calculate the geothermal gradient, which is typical for North-East America (Blackwell and Richards 2004). The idea was to account for the increase of ground temperature that is expected with boreholes of different lengths.

Equations 2 and 3 constitute a system with two equations and two unknowns that can thus be solved to find the values of q'_{b} and T_{fo} for a given borehole configuration and set of fluid and ground conditions. The calculations were performed with a Python script and a time of 30 days was considered. Scoping calculations of heat extraction and injection rates between the borehole and the ground for time-varying between 1 and 300 days showed that the heat exchange rate stabilizes after approximately 30 days, both in heating and cooling mode for all the borehole configurations.

Using this problem-solving strategy, maximum heat extraction and injection rates in the ground were first calculated for 152.4 m (500 ft) long boreholes and a ground TC of 2.5 W/m/°C. Then, the impact of the borehole length on the GHE performance was assessed by calculating additional heat extraction and injection rates for boreholes of 205.7 m (675 ft) and 259.1 m (850 ft), while keeping the ground TC at a value of 2.5 W/m/°C. Finally, the impact of the ground TC on the performance of the heat exchangers was assessed by carrying out the calculations for 152.4 m (500 ft) long boreholes using a ground TC of 1.6 W/m/°C (typical of moist clay) and 3.4 W/m/°C (typical of granite), in addition to the calculations that were carried out previously with a TC of 2.5 W/m/°C (typical of saturated sandstone). The values of ground TC were chosen to represent ranges commonly associated to geological materials (Clauser 2014).

In this second part, the VersaGLD software (Gosselin and Lamarche 2018) was used to do sizing calculations considering our four GHE configurations (Table 1) in order to evaluate borehole length reduction that can be achieved with a larger pipe diameter. The thermal load profile of a typical high-school building in the climate conditions of Boston was selected for the sizing calculations (National Renewable Energy Laboratory, 2014). Peak heating loads were clipped out to balance the average yearly heating and cooling loads assuming that 75% of the heating requirements would be covered by the geothermal system and the remaining 25% would be covered by an auxiliary heating system.

The mean yearly, maximum monthly, and peak hourly heating and cooling loads calculated from the clipped hourly building loads are presented in Table 2. The loads were entered in VersaGLD to calculate the required length of GHE with the three-pulse approach proposed in the ASHRAE handbook (ASHRAE 2015). Similar to part 1, the finite line source equation (Lamarche and Beauchamp 2007) was used for the thermal response function and the multipole model (Claesson and Hellström 2011) for the borehole thermal resistance. A period of 10 years was used for the mean yearly load, of 30.44 days for the monthly load and of 6 hours for the peak hourly load. A ground TC of 2.5 W/m/°C was selected for all sizing calculations to represent average ground conditions. The strategy used for the sizing calculations was to add boreholes to the borehole field until the length of the individual borehole was close to 152.4 m (500 ft), which is the target drilling length. Borehole horizontal spacing was assumed to be 6 m and boreholes were placed in a rectangular or square grid.

Table 2 – Mean yearly, maximum monthly, and peak hourly loads of a typical high-school building considered for sizing calculation.

Load	Units	Cooling	Heating
Mean yearly load	kW	-98.36	182.49
Max. monthly load	kW	-307.02	412.06
Peak hourly load	kW	-810.93	959.58

The initial ground temperature was again calculated with equation 5 and was 12.40°C for a borehole length of 152.4 m (500 ft). Based on this value, the entering water temperature at the heat pump inlet was set to -1°C in heating mode and 28°C in cooling mode, which is in agreement with the recommendations in ASHRAE (2015). The calculated borehole length requirements were obviously longer in heating mode for this heating dominated building and were thus compared below.

A first comparative analysis was conducted by fixing the conditions on the heat pump side. More specifically, the total flow rate of the heat carrier fluid and the COP were set to the same values for the four different GHE configurations. The total flow rate of the heat carrier fluid was set to 76.70 L/s, a value that ensured turbulent flow in both heating and cooling mode for all pipe sizes. The COP in heating and cooling mode were set to a value of 3.1 and 4.7, respectively, based on the energy efficiency requirement for geothermal heat pump of the Energy Star program. A second comparative analysis was conducted by using variable conditions on the heat pump side. The COP values in heating and cooling were calculated in VersaGLD from performance data of a high efficiency and high capacity commercial water-to-water heat pump (model TMW840; ClimateMaster, 2016). The total flow rate of the heat carrier fluid was optimized in order to minimize the total length of each GHE, while respecting the minimum and maximum flow requirements of the heat pump. Although this case can be more realistic, the results are difficult to compare with each other because multiple factors are then causing changes in total borehole length. It is then difficult to highlight the impact of the pipe diameter on the global results.

RESULTS

Complete results for this study are presented in a report prepared by Gosselin et al. (2021) that is freely available at INRS library while most interesting results are summarized in the four tables below.

Under a constant borehole length (152.4 m; 500 ft), an average ground TC (2.5 W/m. /°C) and the use of HDPE SDR-11 pipes, the double loop 1.5 is by far the most efficient configuration, with heat extraction and injection rates per unit length that are 15.7% and 16.5% larger than those calculated for the single loop 1.25 and 9.8% and 10.1% larger than those calculated for the single loop 2 (Tables 3 and 4). This is explained by the fact that the double loop 1.5 configuration offers a heat exchange pipe surface that is 2.28 greater than that of the single loop 1.25 and 1.6 greater than that of the single loop 2. Analytical calculations also showed that using larger single U-pipe allowed performance gains, with heat extraction and injection rates per unit length that are 5.4% and 5.8% greater for the single loop 2 than those calculated for the single loop 1.25. Results were similar when comparing the performance of GHE with a longer borehole. For the three lengths considered (152.4 m – 500 ft, 205.7 m – 675 ft and 259.1 m – 850 ft), the double loop 1.5 is always the most efficient configuration. However, the difference between the heat extraction and injection rates per unit length calculated between each configuration become less important as the length of the borehole increase. For example, the difference between the heat extraction rates per unit length calculated for the double loop 1.5 and the single loop 1.25 configuration is 15.7% for 152.4 m (500 ft) long boreholes, 15.1% for 205.7 m (675 ft) long boreholes, and 14.4% for 259.1 m (850 ft) long boreholes. Again, results were similar when comparing the performance of GHE under different ground TC. However, the relative performance increase of the double loop 1.5 compared to the other configurations becomes larger when the ground TC increases. For example, the difference between the heat extraction rates per unit length calculated for the double loop 1.5 and single loop 1.25 configuration is 14.4% when the ground thermal conductivity is 1.6 W/m/°C, 15.7% when it is 2.5 W/m/°C, and 16.8% when it is 3.4 W/m/°C.

Table 3 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 2.5 W/m /°C and 152.4 m (500 ft) long boreholes.

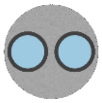
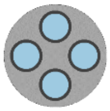
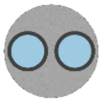
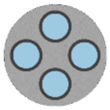
Parameter	Units	Single loop 1.25	Single loop 1.5	Single loop 2	Double loop 1.5
Scale drawing	-				
R_{b}^{*}	m.°C /W	0.094	0.094	0.089	0.064
q_{b}'	W/m	36.61	37.35	38.57	42.36
$\Delta q_{\mathrm{b}}'$	%	0	2.0	5.4	15.7

Table 4 – Ground heat injection rates (cooling) calculated with a ground thermal conductivity of 2.5 W/m/°C and 152.4 m (500 ft) long boreholes.

Parameter	Units	Single loop 1.25	Single loop 1.5	Single loop 2	Double loop 1.5
Scale drawing	-				
R_{b}^{*}	m.°C /W	0.092	0.091	0.085	0.060
q_{b}'	W/m	-43.15	-44.07	-45.65	-50.26
$\Delta q_{\mathrm{b}}'$	%	0	2.1	5.8	16.5

Results for sizing calculations of the typical school building in Boston indicated that under average ground conditions and a fixed flow rate entering the heat pump, the double loop 1.5 remains by far the most efficient configuration with a total borehole length that is 22.3% lower than that calculated for the single loop 1.25 (Table 5). Sizing calculations additionally showed the performance gained by using larger pipes with a total borehole length for the single loop 2, which is 9% lower than that calculated for the single loop 1.25 and 5.5% lower than that calculated for the single loop 1.5. Results obtained for the comparative analysis with variable heat pump conditions remain similar, with the double loop 1.5 being the most efficient configuration and larger pipes for single loop configurations offered a reduction of total borehole length (Table 6). The difference between the total borehole lengths calculated in Table 5 and

Table 6 can be attributed to two main factors. First, larger COP values were obtained in the second case compared to the first (between 4.35 and 4.46 in heating and 5.25 and 5.79 in cooling for the second analysis). A more efficient heat pump resulted in longer boreholes for such a heating dominated building. Second, the optimization of the flow rates in the second analysis resulted in substantially lower volumetric flow rates in the single loop 1.25 (50.47 L/s) and single loop 1.5 (56.78 L/s) compared to the single loop 2 (69.40 L/s) and the double loop 1.5 (100.94 L/s) configurations. Larger flow rates result in a heat pump that is again more efficient. For example, the heating COP for the double loop 1.5 and the single loop 2 was 4.46 and 4.40. On the other hand, the COP of heating for the single loop 1.5 and the single loop 1.25 was 4.35 and 4.34. Moreover, larger flow translates into a smaller temperature difference between the fluid entering and leaving the heat pump. However, this can be compensated by increasing the length of the GHE to decrease the total number of boreholes, but that was not done in the second analysis to keep comparison simple.

Table 5 – Borehole length with fixed conditions on the heat pump size.

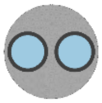
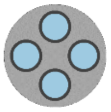
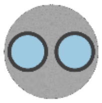
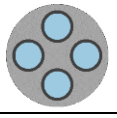
Parameter	Units	Single loop 1.25	Single loop 1.5	Single loop 2	Double loop 1.5
Scale drawing	-				
R_b^*	m·°C/W	0.091	0.090	0.084	0.058
N_{b}	-	85	82	77	67
L_{b}	m	152.2	151.9	152.8	149.9
L total	m	12937	12459	11768	10046
ΔL total	%	0	-3.7	-9	-22.3

Table 6 – Borehole length with variable conditions on the heat pump size.

Parameter	Units	Single loop 1.25	Single loop 1.5	Single loop 2	Double loop 1.5
Scale drawing	-				
R_{b}^*	m·°C/W	0.100	0.098	0.092	0.062
N_{b}	-	98	97	96	88
L_{b}	m	153.3	152.3	152.4	152.8
L total	m	15022	14771	14635	13444
ΔL total	%	0	-1.7	-2.6	-10.5

DISCUSSION AND CONCLUSIONS

Increasing the GHE pipe diameter and/or using a double U-pipe configuration appear to be readily applicable improvements that are simple to implement, especially when compared to modifying the pipe material (Gosselin et al. 2017) or opting for a coaxial GHE configuration requiring numerous pipe fusions in the field (Raymond et al., 2015). GCHP system installers often prefer the ease of single and double loop installations that are compatible with a large pipe diameter and where pipes are rapidly lowered in boreholes for which there is no pipe fusion except for the bottom U-bend and the connection at surface. Considering the results obtained in this study, opting for large diameter pipes can provide increased thermal performances of GHE, especially when choosing a double U-loop configuration. Adjustments maybe be needed when designing the ground loop that would require large valves and pump sizes.

In fact, the performance of four different GHE configurations was compared in this study under various conditions to highlight gains associated with large diameter pipes. Those are single loop GHE made of HDPE and having a nominal pipe diameter of 1.25, 1.5 and 2 inches as well as double loop GHE made of HDPE and having a nominal pipe diameter of 1.5 inches. Increasing the pipe diameter in all configurations reduced the borehole thermal resistance that is multiplied to the peak ground load when performing sizing calculations, which resulted in borehole length savings attributed to the ground power coverage. Sizing calculations were made over a period of ten years, but results are expected similar if the duration of the yearly ground load is increase. Overall, the double loop 1.5 GHE is by far the most efficient solution for all situations. For the single loop configurations, the use of larger pipe size always resulted in better performances, which confirmed our original working hypothesis, but the gain is not as important as when using a double versus single loop configuration. This study further demonstrated the importance of borehole length, ground TC and heat pump conditions on the calculated GHE performances. In all cases, the conclusions remained similar. Even with deep boreholes, high ground TC or favorable flow conditions for the heat pump, the double loop 1.5 configuration is the one that best performed. Whether this thermal performance gain can translate into financial savings to reduce the installation cost of a GCHP is the next question to tackle and for which practitioners may have an opinion to share during this IGSHPA conference.

ACKNOWLEDGMENTS

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NOMENCLATURE

C = specific heat capacity (J/kg/°C)
Fo = Fourier number (-)
G = Thermal response function (-)
k = thermal conductivity (W/m/°C)
L = length (m)
$\dot{m}$ = mass flow rate (kg/s)
N = number of (-)
q' = heat exchange rate per unit length (W/m)
q'' = Earth heat flux (W/m^2)
R^* = effective fluid-to-ground thermal resistance (°C·m/W)
T = temperature (°C)

Subscripts

b = borehole
f = fluid
g = ground
i = entering
o = leaving
0 = initial condition
4m = 4 m depth

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