Evaluation of Vertical and Horizontal Geoexchange Systems

TECHNICAL BRIEF

Heating and Cooling System Series

Geoexchange systems are a sustainable space heating and cooling alternative that is gaining broader adoption in both residential and commercial sectors. A geoexchange system keeps a building warm in winter by using heat energy extracted from the ground. The process is reversed in summer when a building is kept cool by rejecting excess heat energy back into the ground. Heat transfer with the ground is made possible by a fluid circulating though buried pipes, referred to as a ground loop.

In Toronto, heating a single-family residence using a geoexchange system rather than a conventional natural gas furnace can, in some cases, yield annual greenhouse gas emissions reductions comparable to taking an average car off the road for an entire year (CGCR, 2010).

Photo Credit:Ruben de Rijcke

This study evaluated the performance of a geoexchange system used to heat and cool a semi-detached LEED Platinum house located at the Toronto and Region Conservations' Living City Campus in Vaughan, Ontario. The system was uniquely equipped with a vertical and horizontal ground loop and the capability to operate with both loops in parallel or a given loop individually. Previous research investigated the performance of the system when it was coupled to the horizontal ground loop. The seasonal heating and cooling mode coefficients of performance (COPs) for a typical year when using the horizontal loop were found to be 3.0 and 4.9, respectively.

For comparison, the research presented in this technical brief investigated the performance of the system when coupled to the vertical loop. In this configuration, the heating and cooling mode COPs were 3.0 and 4.5 respectively. It must be noted that these were not seasonal values but rather, values determined directly from performance data taken over two to three weeks of testing at the end of the heating season and the beginning of the cooling season. They are in reasonable agreement with manufacturer specifications for the heat pump. Cooling mode performance testing was also done with both the horizontal and vertical loops operating in parallel with equal flow. During the testing period, the loops rejected equal amounts of heat to the ground, suggesting comparable cooling mode performance.

Differences in experimental design made it difficult to draw concrete conclusions from the horizontal and vertical loop experiments. Based on the information collected, it seems likely that the performance of the horizontal and vertical loops is not notably different. A similarity in performance could be explained by the horizontal loop's greater volume compensating for its initially poorer entering source temperatures. It is recommended that further testing and model simulations be conducted under controlled conditions to provide a more definitive comparison.

INTRODUCTION

Geoexchange systems are widely considered to be a more sustainable alternative to conventional heating and cooling systems because they are fueled by low carbon electricity sources (Ontario Energy Board, 2013) and are able to deliver or remove as much as four or five units of heat energy for every unit of electrical energy consumed. The ratio of heat energy delivered or removed over electrical energy consumed is termed the coefficient of performance (COP). In a geoexchange system, heat energy is removed from the ground when heating is required and rejected back to the ground when cooling is required. This is most commonly accomplished by a long closed loop of piping buried underground in either a vertical or horizontal configuration. This loop allows heat transfer between the ground and a fluid circulating through the loop.

A vertical loop (Figure 1) is typically more expensive to implement because it requires specialized equipment for drilling into the ground at depths that can exceed 80 m. Vertical loops have the potential to perform better than horizontal loops because of the stable ground temperatures at such depths. It is often the only option in space-constrained urban settings. A horizontal loop (Figure 2) spreads out over a large horizontal area and it is typically less expensive to implement because it only requires relatively shallow surface trenching. It suffers from adverse seasonal fluctuations in ground temperatures occurring near the ground surface that may reduce performance. However, in areas with high water tables, the thermal conductivity of soil is increased and this may help enhance system performance. A vertical or horizontal loop may perform equally well provided the loops are sized appropriately. This normally means that the vertical loop is smaller in volume than the horizontal loop.

There is a lack of research that experimentally examines both types of ground loop simultaneously for the same study site. This study attempted to fill that knowledge gap by experimentally comparing the performance of a horizontal loop with that of a vertical loop, each being attached to the same ground source heat pump and distribution system.

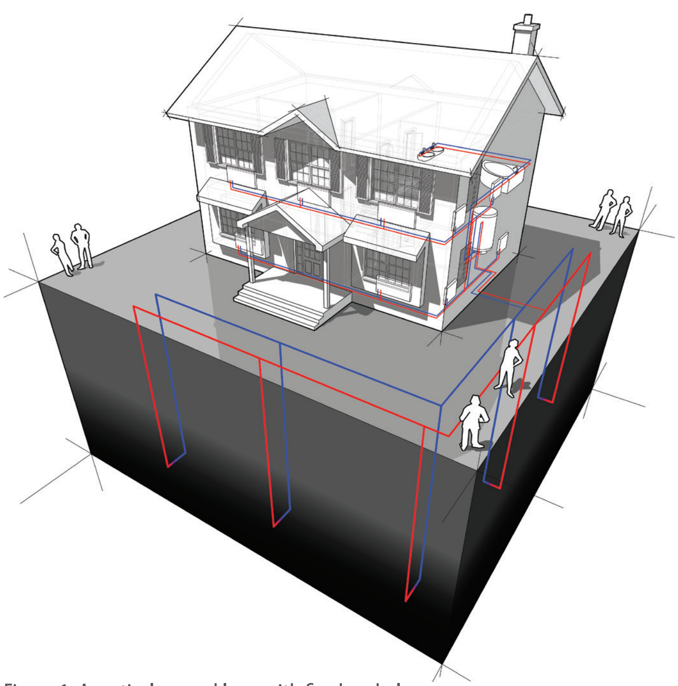

Figure 1. A vertical ground loop with five boreholes.

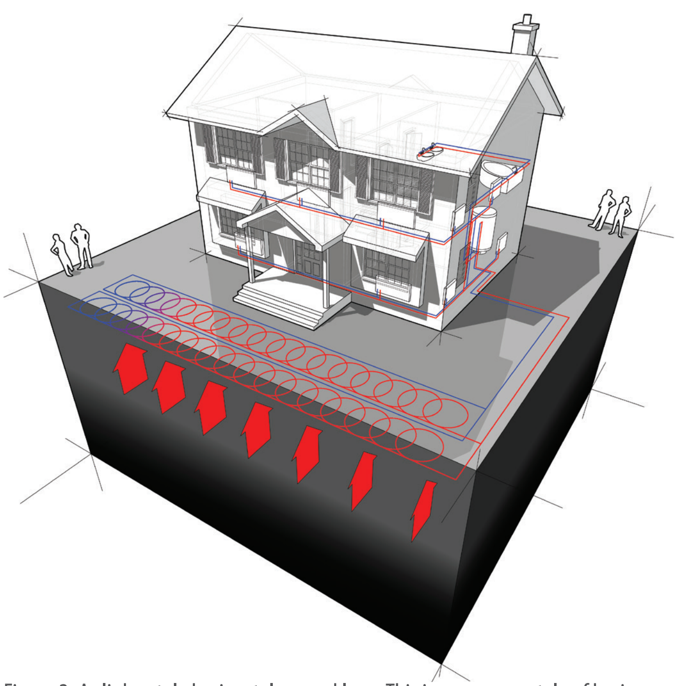

Figure 2. A slinky-style horizontal ground loop. This is a common style of horizontal ground loop, however, in this study the horizontal loop is a J-style ground loop with a long length of tubing running out and back in the shape of a large "J."

STUDY SITE

This study was conducted at the Toronto and Region Conservation's Archetype Sustainable House located at the Living City Campus in Vaughan, Ontario (Figure 3). The technologies implemented into House A showcase current sustainable practices, while the technologies in House B present energy conservation practices and technologies expected to become prominent in the near future. The semi-detached House B investigated in this research is described briefly in Table 1. Although the House is not utilized by full-time occupants, it is heated and cooled much like a typical house The house has been designed as an energy conservation and sustainable technology test facility, and the geoexchange system was uniquely equipped with a fully instrumented horizontal and vertical ground loop (Table 2). The system has been configured to allow for both parallel and individual operation of the two loops and is powered by a Water Furnace heat pump with 3.5 tons nominal capacity (Figure 4a). The heat pump charges a buffer tank used for radiant floor heating and forced air cooling.

Figure 3. Archetype Sustainable House - House B is in the forefront.

Table 1. Archetype House B summary.

Archetype House B	
Orientation	South facing
Stories	3
Floor Area (m^2)/(ft^2)	232/2500
Seasonal Heating load (kWh)*	18764
Seasonal Cooling load (kWh)	2459

* The house heating and cooling loads were obtained from pg. 100 of (Safa, 2012) and are the result of calibrated TRNSYS simulations.

Table 2. Horizontal and vertical loops specifications

Parameter	Vertical Loop	Horizontal Loop
Number of loops	2	2
Depth of each loop (m)/(ft)	76.2/250	1.83/6
Length of each loop (m)/(ft)	152/500	366/1200
Nominal Diameter (in)	1	1.25
Material	HDPE 4710	HDPE 3408
Total Volume of both loops (L)/(US gal)	192/51	732/193
Shape	U-loop	J-loop
Fluid	20% Propylene Glycol	20% Propylene Glycol

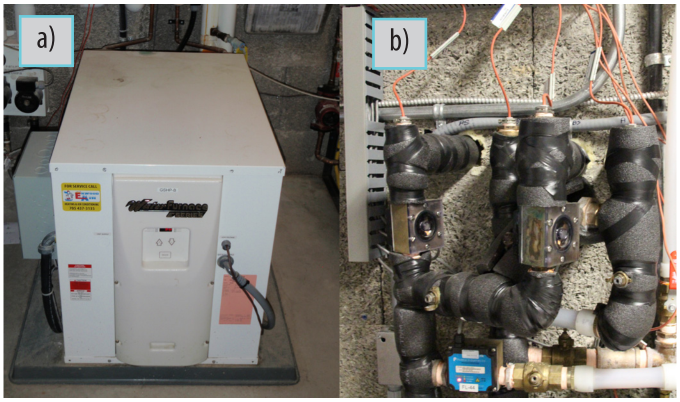

Figure 4. a) Waterfurnace EW042 ground source water-to-water heat pump. b) Instrumentation is shown for vertical and horizontal ground loops entering the building in the basement of Archetype House B.

APPROACH

Heating mode performance monitoring with the system coupled to the vertical loop took place between May 14th and June 4th, 2013. Cooling mode performance monitoring with the system coupled to the vertical loop took place between June 21st and July 8th, 2013. Additional cooling mode performance monitoring with both the vertical and horizontal loop operating in parallel took place between July 19th and August 7th, 2013. Full season performance testing was not possible due to the time constraints of the study. During the monitoring periods, the geoexchange system was allowed to run according to its normal control logic with the pumps interlocked to the compressor unit. Several key points were monitored that were later used to calculate the COP and other performance indicators. COP results presented in this report include the buffer tank circulator pump, ground loop circulator pump and compressor unit power consumption. The estimated uncertainty in the COP calculations is ±9%. Vertical loop COP results were compared with a previous study when the system was coupled to the horizontal loop (Safa, 2012).

Figure 5 shows the monitoring sensors and locations . Temperature was measured using Pt500 RTD matched-pair probes from Kamstrup mounted within thermal wells. Flow rate was measured using impeller- style flow meters from Proteus Inc. Power sensors were Wattnodes from Continental Control Systems. Temperature sensors were calibrated using a Sika TPM165S temperature calibrator and flow measurements were calibrated using an Elster Amco water meter. To the left of the heat pump (Figure 5) is the entering (T17) and leaving (T16) load temperatures (ELT and LLT), load circulator pump power consumption and load flow rate (FL6). To the bottom right of the heat pump in the schematic is the entering (T64) and leaving (T65) source temperature (EST and LST) and flow rate for both the vertical (V-loop) (FL 42 & 43) and horizontal (H-loop) (FL 44) loops as well as the circulator pump power consumption.

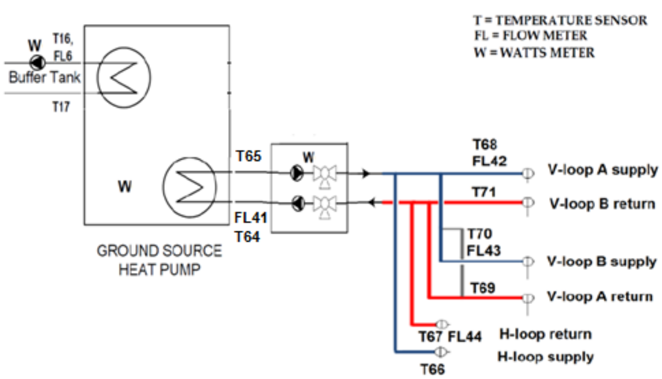

Figure 5. Schematic of performance test monitoring points.

FINDINGS

The vertical loop geoexchange heating and cooling mode COPs during the testing period were 3.0 and 4.5, respectively. In other words, one unit of electricity produced 3.0 heating units during the heating season and 4.5 cooling units during the cooling season. Figure 6 shows, as daily averages, the percentage of time that the unit was operational (Part Load Percentage), the average cycle time as well as the heat removed/delivered and electrical power consumption during both the heating and cooling mode testing periods. The cycle time is defined as the quantity of time elapsed between when the unit turns on to begin providing heating or cooling and then subsequently turns off. On any given day there may be many on/off cycles. The relationships generally meet expectations of how the system should perform. During the cooling season, ambient air temperatures were correlated with power consumption, heat/cooling output and heat pump operation time, while it was inversely correlated in the heating season. Daily COP averages varied between 2.6 and 3.1 for heating mode, and between 4.2 and 4.8 for cooling mode. In cooling mode, it appeared that larger daily average cooling loads, and longer cycle times, were associated with lower COPs. It might be expected that shorter average cycle times would have lower COPs because the losses associated with starting and stopping the compressor would be greater in proportion to the heat rejected during the cycle. However, the opposite was observed: longer cycle times were correlated with lower COPs. This is likely due to a net heat gain in the ground loop fluid that had a larger effect on longer cycle times. This is described in greater detail below.

The average vertical loop heating mode COP of 3.0 was comparable to the manufacturer rated COP of 2.9 to 3.0. Note that the manufacturer specifies COP at a single operating point with a given entering source temperature (EST), entering load temperature (ELT), load flow rate and source flow rate, while the experimental value presented here is determined over the entire test period. EST and ELT measuring points are explained in the Study Approach section. The manufacturer specification is determined for an EST of 0 ^{0}C, an ELT of 40 ^{0}C, a source flow rate of 11 - 16.5 GPM and a load flow rate of 7 – 16.5 GPM (Water Furnace Manual). The experimental parameters were close to, or within the manufacturer-specified ranges, as EST was 1 – 4 ^{0}C, the ELT was 40 – 45 ^{0}C, the source flow rate was 12.7 GPM and the load flow rate of 13.3 GPM. As a result, the manufacturer and measured COPs of 2.9 and 3.0, respectively, are comparable and suggest that the unit was performing as rated in heating mode. The Energuide COP rating for ground source heat pumps during the entire heating season was slightly higher than observed, at 3.3.

The average vertical loop cooling mode COP of 4.5 was higher than the manufacturer rated COP of 3.6 to 3.8. This may be partly explained by the relatively cooler source temperatures during the monitoring period when compared with the manufacturer's testing conditions. The manufacturer specification is determined for an EST of 25 ^{0}C, ELT of 12 ^{0}C, a source flow rate of 11 - 16.5 GPM and a load flow rate of 11 – 16.5 GPM (Water Furnace Manual). The experimental EST was 16 – 21 ^{0}C, the ELT was 3 – 11 ^{0}C, the source flow rate was 12.7 GPM and the load flow rate was 13.3 GPM. Figure 7 shows that, in cooling mode, higher ELTs are associated with higher COPs and higher ESTs are associated with lower COPs. It is believed

Figure 6. a) Daily percentage of cycled time and average cycle time for both heating and cooling monitoring periods. b)Daily total heat removed or delivered, total electricity consumed and COP for both heating and cooling monitoring periods.

that the lower experimental EST caused the higher experimental COP. The Energuide rating for ground source heat pumps during the cooling season is expressed as a Seasonal Energy Efficiency Ratio (SEER) of 14.1, equivalent to a seasonal average COP of 4.1.

The heating and cooling mode COPs associated with the vertical loop were 3.0 and 4.5 respectively, and those for the horizontal loop, on the same system, were 3.0 and 4.9, respectively (Safa, 2012)* . However, differences in the experimental conditions made it difficult to determine with certainty which loop performs better. Much of the uncertainty can be explained by differences in experimental design and measurement periods. In the horizontal loop study, experimental data was obtained during 1 to 2 months of the heating and cooling seasons. This information was then used to conduct TRNSYS simulations to determine the seasonal heating and cooling COPs for a typical year. These simulated COPs were subsequently compared with the COPs determined from the vertical loop study described in this report; however, the vertical loop study used COPs calculated from 2 to 3 weeks of heating and cooling data without any additional modeling. It follows that the comparison is not strictly fair and must therefore be treated more qualitatively than quantitatively. It seems likely that if there is any difference in performance between the horizontal and vertical loop systems, that the difference may not be drastic. A similarity in performance could be explained by the horizontal loop's greater volume compensating for its initially poorer

* Note that the COP values of 3.0 and 4.9 were calculated from Table 22 in Safa (2012) using the compressor, ground loop circulator pump and buffer tank circulator pump power consumption.

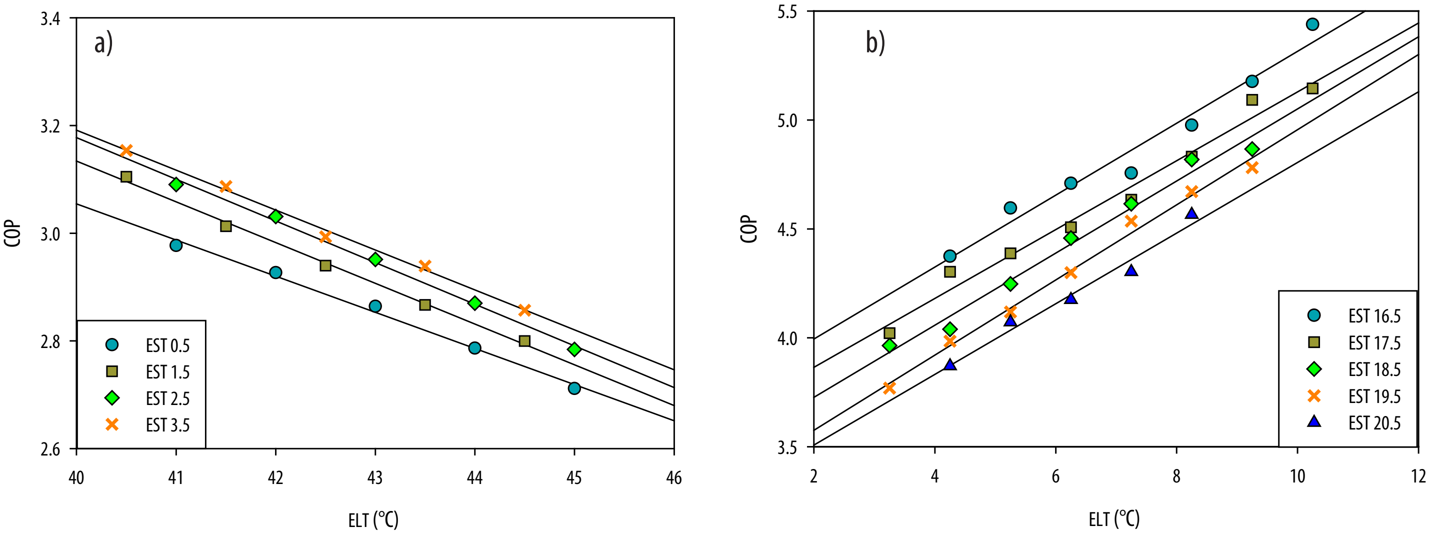

Figure 7. a) Heating mode COP increases as ELT goes down and EST goes up. b) Cooling mode COP increases as ELT goes up and EST goes down.

ESTs. The validity of these observations would need to be determined through further experimental work and/or TRNSYS modeling.

The vertical and horizontal ground loops showed comparable cooling mode performance when operated in parallel. The combined daily average heat rejected to the ground by the vertical and the horizontal loops from July 19th to August 7th, when both loops were operated in parallel with equal flow rates (8.5 GPM), was 15.5 kWh. Individually, the average heat rejected by the vertical and horizontal loops was 7.89 and 7.58 kWh, respectively. This suggests that their cooling mode performance is comparable. The vertical loop had more heat transfer per unit area. This was mainly a result of the lower ground temperatures at greater depths. However, also important is the improved turbulent flow profile in the vertical loop due to its smaller diameter. Turbulent flow is ideal for convective heat transfer. It is described by its Reynolds number which takes into account factors such as flow rate, pipe cross-sectional area, fluid density and viscosity. The Reynolds number of the horizontal loop was 4400 while that for the vertical loop was 5540, where higher Reynolds number indicates increasingly turbulent flow. While the vertical loop had more heat transfer per unit area, the horizontal loop had more area and these factors appeared to balance out. A subsequent experiment was conducted where both loops had a Reynolds number of 4840, but different flow rates. The vertical loop flow rate was 7.4 GPM while the horizontal was 9.2 GPM. No appreciable difference in heat rejection was observed.

The COP of the vertical loop system during heating and cooling modes was shown to be dependent on the entering source temperatures and entering load temperature. The effects of the entering load and source temperatures on the vertical geoexchange system COP is presented in Figure 7. As expected, heating season COPs increased as ELTs decreased and ESTs increased. The reverse occurred during the cooling season. During both seasons, the lower the difference between source and load temperatures, the higher the COP. This difference is termed the temperature “lift” and a geoexchange system operates most efficiently with a low lift. In heating mode, lift is reduced by raising the EST or decreasing the ELT. The ELT can be decreased by operating the system at a lower set point temperature but this may not be ideal in many applications. More interesting is the integration of other renewable technologies, such as solar hot water heating or solar PV, to act in a preheating capacity to reduce lift by increasing the EST. It may well be that an optimal sustainable heating solution does not come from any one technology, but rather from a hybrid system of complementary technologies.

Potential improvements in performance could be achieved by using a variable capacity or two-stage ground source heat pump. During the cooling mode performance testing from July 19th to August 7th, both loops were operated in parallel with the same flow rate. A representative on-cycle is shown from that period in Figure 8. It is apparent that the vertical loop EST was initially lower than the horizontal loop EST and, therefore, is expected to have a higher COP. However, the vertical loop was not able to reject heat back to the ground at a fast enough rate. This resulted in a net heat gain that forced the EST to rise and COP to fall over time. This may explain why longer cycle times are associated with lower

COPs in Figure 6. However, if the heat pump capacity was reduced, heat could be rejected at a slower rate without having a net heat gain. The EST would not increase during the cycle and the average COP would be higher. To remove an equivalent amount of heat from the building, the heat pump would then need to operate at lower capacity for a longer period of time. This would only be a successful heating or cooling strategy if the load could actually be met by continuous part-load operation. This would normally be the case during the shoulder months but such a strategy would not work during peak heating and cooling months. Two-stage heat pumps, with the ability to operate at two different heating capacities, have been available for a while. More advanced variable capacity heat pumps are also slowly becoming available. Both these technologies have the potential to enhance performance by operating at part-load capacities, thereby mitigating or preventing any net heat gain in the ground loop fluid. As suggested in Figure 6, it may also be possible to achieve COP enhancements with a standard on/off heat pump by operating it with a more optimal cycle time.

Vertical loop systems cost more than equivalently sized horizontal loop systems. In Ontario, the average cost of a geoexchange system with a closed vertical ground loop is $8,132 per ton, while that of a system with a closed horizontal ground loop is $6,100 per ton (CGCR, 2012). The vertical loop option is $2,000 per ton, or approximately 33%, more expensive than the horizontal option. That means that a 3.5 ton system may, on average, cost $21,350 if it uses a horizontal loop or $28,462 if it uses a vertical loop, a difference of $7,112. If the difference in performance between equally sized vertical and horizontal loops is not appreciable then it might be difficult to justify the added cost of a vertical loop if a horizontal loop was possible given the constraints of the site. However, it is worth noting that, in many cases, a vertical loop is the only option due to space considerations. Although single-lot geoexchange systems have relatively high implementation costs, the cost of both vertical and horizontal loops could be substantially reduced if several adjacent systems are constructed at the same time. This is often the case for new subdivisions designed to condition homes by geoexchange.

CONCLUSIONS

This study indicated that the geoexchange system operated in reasonable agreement with the manufacturer performance specifications, regardless of the orientation of the ground loop. This helps to build confidence in the technology.

Both loops rejected the same amount of heat to the ground when they operated in parallel in cooling mode, suggesting comparable performances. While the vertical loop had more heat transfer per unit area, the horizontal loop had larger area and the combined influence of these factors resulted in similar heat rejection performance.

Differences in testing conditions between the previous study examining horizontal loop performance and the current study examining vertical loop performance meant that there was no definitive conclusion regarding which loop performed better. However, the COP numbers from each study were comparable, perhaps suggesting that there are at least no drastic differences between the performances of each loop. This is a reasonable result and it suggests that both loops were equivalently sized for the system.

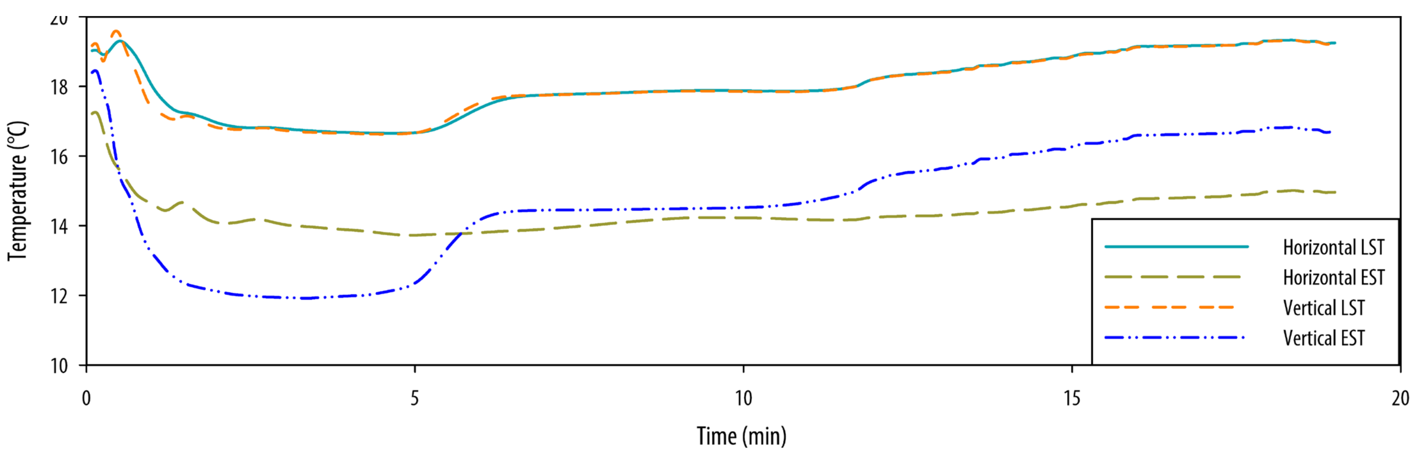

Figure 8. The entering source temperatures (ESTs) and leaving source temperatures (LSTs) for each ground loop averaged over all cycles from July 19 to August 7, 2013, with both the horizontal and vertical ground loops operating in parallel with equal flow. Note that it takes 5 minutes for the vertical loop to complete one full circulation while it takes 23 minutes for the horizontal loop because it is larger in volume.

During the heating season, the system delivered more than three units of heat energy for every unit of electrical energy consumed. This is further proof that geoexchange systems require less energy than conventional systems to deliver an equivalent amount of heating. In Ontario, the electricity used to power these systems is increasingly derived from sustainable sources. Based on current electricity generation sources in Ontario, it is estimated that a similar sized geoexchange system would reduce annual greenhouse gas emissions by 3549 kg eCO_2. These emissions reductions are on the same scale as reductions obtained by taking an average car off the road for an entire year (CGCR, 2010). As Ontario continues to invest in cleaner energy, the emissions reductions associated with geoexchange systems will rise in tandem.

REFERENCES

Alzahrani, Waleed Saeed (2014) Experimental study of the performance of a vertical and a horizontal ground loops couples to a ground source heat pump system. Master of Applied Science, Ryerson University.

Canadian Geoexchange Coalition Report (CGCR) (2010) Comparative Analysis of Greenhouse Gas Emissions of Various Residential Heating Systems in the Canadian Provinces, p. 28. Note: Average car emissions in Canada cited to be 3,360 eq. CO_2/year within report.

Canadian Geoexchange Coalition Report (CGCR) (2012) The State or the Canadian Geothermal Heat Pump Industry: 2011 Industry Survey and Market Analysis. p. 88.

Ontario Energy Board (2013) Ontario's System-Wide Electricity Supply Mix: 2013 Data. Accessed online June 05/2014: http://www.ontarioenergyboard.ca/oeb/_Documents/Regulatory/2013_Supply_Mix_Data.pdf

Safa, Amir Alizadeh (2012) Performance analysis of a two-stage variable capacity air source heat pump and a horizontal loop coupled ground source heat pump. Master of Applied Science Thesis, Ryerson University.

Water Furnace EW Series Installation Manual. p . 25. Accessed online June 05/2014. http://www.waterfurnace.com/literature/eseries/IM1469.pdf

Cover Photo Credit - Idaho Geothermal (www.idahogethermal.com)

For more information on STEP's other projects, visit us online at www.sustainabletechnologies.ca

This technical brief was prepared by the Toronto and Region Conservation Authority's Sustainable Technologies Evaluation Program (STEP) based on an M. A.Sc thesis completed by Waleed Alzahrani in 2014, under the supervision of Dr. Wey Leong at Ryerson University. The research was conducted collaboratively between Ryerson University and STEP, with funding support from Toronto Atmospheric Fund, Region of Peel, York Region and the City of Toronto, and in kind support from Beatty Geothermal Inc. For more information about this project, please contact STEP@trca.on.ca.