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FIELD-SCALE EXPERIMENTAL ANALYSIS OF HELICAL STEEL PILES AS IN-GROUND HEAT EXCHANGERS FOR GROUND SOURCE HEAT PUMPS

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Abstract**—**With the increasing concern of climate change and greenhouse gas emissions, innovative solutions to produce energy via renewable sources are needed. Geothermal energy has the potential to provide heating and cooling to residential and commercial buildings, however, its implementation has been stunted due to high initial costs, longer payback periods, and lesser return on investment. Helical steel piles, mainly used as structural foundations for buildings, have the potential to act as in-ground heat exchangers, producing higher efficiencies than conventional borehole systems at a lower cost. Eight helical steel piles, fitted with plastic tubing for fluid circulation, have been installed in an experimental site in Waterloo, Ontario. Cooling and heating tests have been conducted on the novel system to evaluate the capacity, power consumption and coefficient of performance. This paper presents the results of the peak and steady state capacity tests as well as the limitations experienced.

Keywords-Geothermal; Renewable Energy; Ground Source Heat Pumps; Helical Steel Pile; Heat Transfer; Greenhouse Gas Emissions; Thermofluids

I. INTRODUCTION

With increasing greenhouse gas (GHG) emissions, new and innovative solutions to provide energy via renewable sources are needed. Currently in Canada, energy used for space and water heating accounts for 80% of consumption in the residential sector and 63% in the commercial sector with natural gas as the main energy source. Sustainable energy alternatives are plagued by intermittency (wind, solar) or high capital cost expenditures and technical constraints [1].

Geothermal energy has been identified as a possible solution for reducing GHG emission. This energy source is used with a ground source heat pump (GSHP) to provide higher efficiencies compared to an air source heat pump system. The conventional GSHP system uses vertical borehole loops of polyethylene tubing, drilled to depths of up to 250 m, to transfer heat with the surrounding soil [2]. Global implementation of this system has been stunted due to high initial costs, longer payback periods, and lesser return on investment [1].

Helical steel piles, mainly used as structural foundations for buildings, have the potential to act as shallow in-ground heat exchangers, significantly reducing installation costs and space requirements compared to the conventional geothermal system. These helical steel piles employ a welded helix and capped tip allowing direct insertion into the soil without pre-drilling. Helical steel piles for low to mid rise structures are typically installed at depths between 6 to 30 meters, which is much shallower than conventional borehole loops. A working fluid is pumped through plastic tubing fitted inside the pile. This allows heat exchange between the working fluid and the steel casing as well as the surrounding soil to achieve the temperature change required by the heat pump [3]. The offset tubing allows for the greatest heat exchange to occur along the length of the pile. In the cooling season, warm fluid exchanges heat with the piles to reduce the fluid temperature and cool the space. In the heating season, cool fluid exchanges heat with the piles to increase the fluid temperature and heat the space [1].

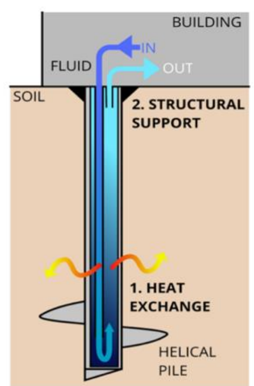

Figure 1. Schematic representation of a pile [1].

An experimental site with eight piles has been installed at the *Eby Rush* Transformer Station in Waterloo, Ontario. Testing is being conducted to develop a technical understanding of the operating principles and optimization methods for a multi-pile heat exchanger system [4].

II. METHODOLOGY

A. Experimental Site

The Eby Rush Transformer Station includes a primary building which houses the station switchgear, a site office, and a storage area for spare distribution cables. The two-level building is approximately 3000 ft^2 with a heat pump located on a utility mezzanine. Since the mid 1990's, the primary building has been conditioned by a 6-ton WaterFurnace Premier 2 heat pump connected to a conventional vertical ground loop array. Records including the exact location and specifications for the ground loop were unavailable, however, a review of the as-built drawings as well as field investigations confirmed the ground loop is vertical and not a horizontal or open-loop system [4].

A new 6-ton Versatec (WaterFurnace) Variable Speed Heat pump was installed to replace the previous heat pump and was metered to measure the performance of the existing ground loop [5]. A pile array composed of 8 piles with an outer diameter of 5.5 inches was installed. Four of the piles were 15 meters in length and the other four piles were 18 meters in length. The piles were spaced 4.25 meters apart to mitigate thermal interference between them and with the ground loop array, as well as work within the space constraints of the site. The pile array was connected with the ground loop using a 3-way electronically activated valve to direct the flow between the two systems (shown as V1 in Fig. 2). To implement this configuration, a brazed plate heat exchanger was added to transfer heat from the pile array to the main loop connected to the heat pump. The existing ground loop array and heat pump operate on a 30% propylene glycol fluid loop, while the pile array operates on a water loop. The system was connected to a data acquisition system (DAQ) installed at the field demonstration to monitor and control the system and determine energy performance of the piles (e.g., active value switches remotely for testing on/off control, variable flow rates, and time of use (TOU) rates). The pile array was separated into two groups of four piles with the flow controlled by 2-way electronically operated valves (shown as V2 and V3 in Fig. 2). Fig. 2 below represents the interface of the pile system, and the sensors present for calculations [4].

B. Testing Procedures

Tests are conducted via a web interface. The valve position for V1 is first altered to direct the flow towards the piles. The set point for the primary building is then inputted based on the building's cooling or heating needs. The test is monitored over its duration and ends once the stopping criterion has been met. To interpret the data, spreadsheet files are downloaded from the web-user interface of the installed data acquisition system and uploaded into MATLAB to first process and synchronize the data and then perform capacity and Coefficient of Performance (COP) post-calculations. The graphs produced are then analyzed to better understand the performance of the pile system.

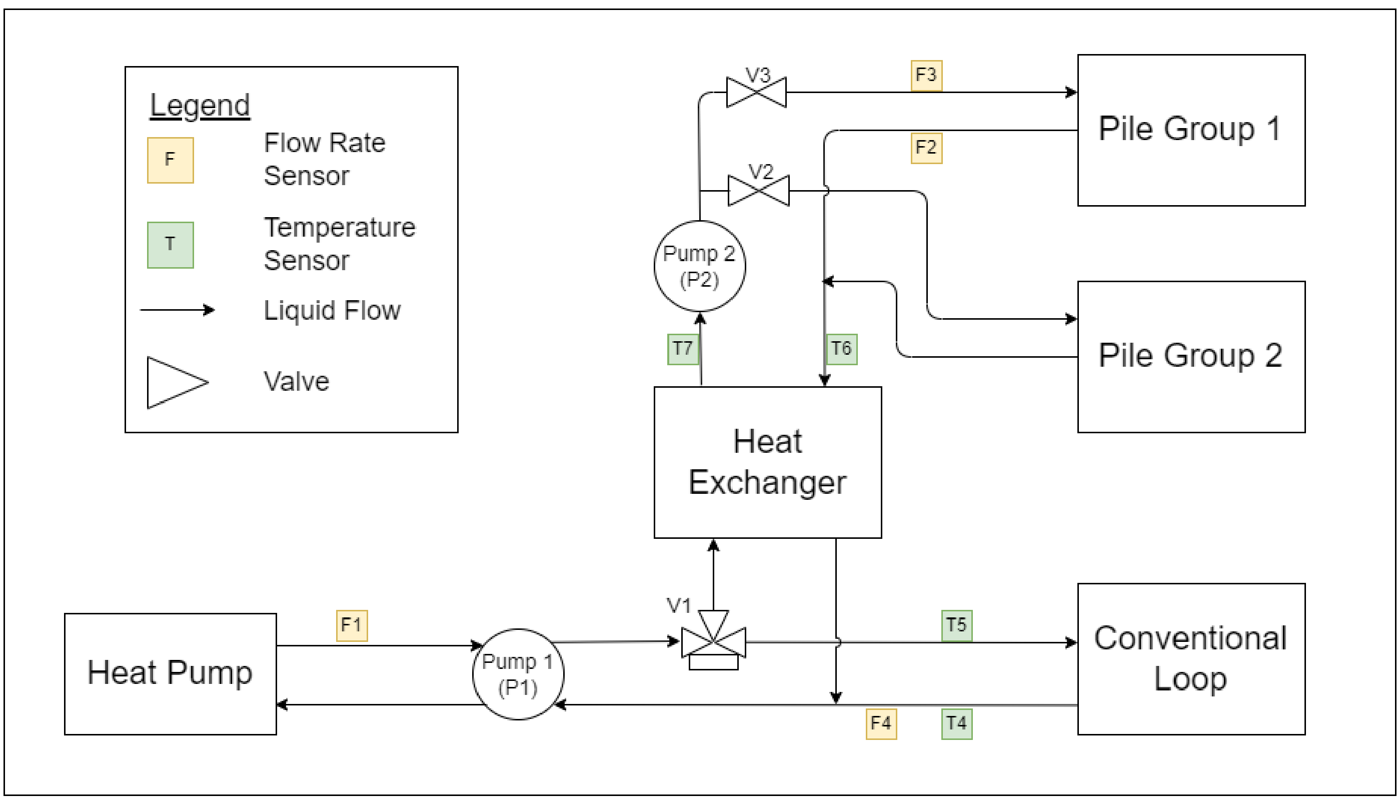

Figure 2. Experimental site DAQ system schematic.

C. Calculations

To characterize the system in cooling and heat mode, it was desired to calculate the overall COP of the heat pump as well as the performance of the pile array and conventional loop individually, expressed as an efficiency. To calculate the overall COP, the following equation was used,

$$COP_{HP} = \frac{TotCapacity_{HP}}{AntifreezeCor \times TotPower_{HP} + P1 + P2} \quad (1)$$

where, $TotCapacity_{HP}$ is the total capacity in Watts (W), *AntifreezeCor* is the antifreeze correction factor and is equal to 0.950 for cooling and 0.854 for heating [5], $TotPower_{HP}$ is the total power used by the heat pump in Watts (W), *P1* and *P2* are the power consumed by the two circulating pumps in the system, respectively, in Watts (W).

Since the pile array and conventional loop have separate flows and the three-way valve allows both systems to operate together, the contribution and power consumed by both systems must be calculated individually to determine their efficiency. The partial power used by the piles and conventional loop was first determined using the equations below [6]:

$$PartialPower_{piles} = \Delta P \times (F1 - F4) = (\tfrac{F1-F4}{F1}) \times TotPower_{HP} \quad (2)$$

$$PartialPower_{ConvLoop} = \Delta P \times F4 = (\frac{F4}{F1}) \times TotPower_{HP} \quad (3)$$

$$\Delta P = \frac{TotPower_{HP}}{F1} \quad (4)$$

where, $PartialPower_{piles}$ is the power consumed by the pile system in Watts, $PartialPower_{ConvLoop}$ is the power consumed by the conventional loop in Watts, *F1* is the flow rate of glycol flowing into the heat pump in m^3/s, *F4* is the flow rate of glycol flowing into the conventional loop in m^3/s, and ΔP is the total pressure losses in the system.

The heat released or extracted was then calculated for the overall heat pump, the pile array, and the conventional loop using the following equations.

$$HRHE_{HP} = (LWT - EWT) \times cpf \times F1 \quad (5)$$

$$HRHE_{piles} = (F2 + F3) \times cpf \times (T_6 - T_7) \quad (6)$$

$$HRHE_{ConvLoop} = HRHE_{HP} - HRHE_{piles} = F4 \times cpf \times (T_5 - T_4) \quad (7)$$

Where *HRHE* is the heat released or extracted across the heat exchanger in Watts (W), *LWT* is the leaving water temperature of the heat pump in Celsius (^oC), *EWT* is the entering water temperature of the heat pump in Celsius (^oC), *cpf* is the specific heat capacity of water with 30% glycol, equal to 2030.21 kJ/kg-K (485 Btu/lb) [5], *F2* and *F3* are the flow rates of water going into pile group 1 and group 2, respectively, in m^3/s, T_6 is the temperature of the water leaving the piles in Celsius, T_7 is the temperature of the water entering the piles in Celsius, T_5 is the temperature of the water entering the conventional loop in Celsius, and T_4 is the temperature of the water leaving the conventional loop in Celsius.

The efficiency (η) of the pile array and conventional loop were then calculated using the following equations, respectively.

$$\eta_{piles} = \frac{HRHE_{piles}}{PartialPower_{piles}} \quad (8)$$

$$\eta_{ConvLoop} = \frac{HRHE_{ConvLoop}}{PartialPower_{ConvLoop}} \quad (9)$$

D. Testing Plan

Cooling tests were conducted in August and September 2021. These included the peak cooling capacity test and the cooling steady state capacity test with varying flow rates. The peak cooling capacity test was conducted on a very hot day representing the maximum cooling load that may be placed on the system. All eight piles were engaged for 7 hours, working to cool the building from 22^{o}C to 18^{o}C. For the cooling steady state capacity test, the test was conducted on a warm day representing an average cooling load for the system. All eight piles were engaged for 6 hours, working to cool the building from 22^{o}C to 20^{o}C. Ten tests were carried out to determine the steady state capacity of the system at various flow rates, beginning with a flow rate through the heat exchanger (to the piles) of 1.26E-5 m^3/s (0.2 GPM) and ending with the entire flow going through the heat exchanger (to the piles) at a flow rate of 8.86E-4 m^3/s (14.04 GPM). These flow rates were determined by taking the difference between the system flow rate (F1) and the flow rate through the conventional loop (F4).

Heating steady state capacity tests were conducted in November of 2021. The tests were run on a cold day where all 8 piles were engaged for 3 hours. The system worked to heat the building from 22^{o}C to 23.3^{o}C. Three tests were conducted with a flow rate of 4.61E-5 m^3/s (0.73 GPM), 1.02E-4 m^3/s (1.61 GPM) and 1.46E-4 m^3/s (2.32 GPM) going through the heat exchanger (to the piles), respectively. The difference in temperature (ΔT), capacity, power consumption and COP were calculated for all cooling and heating tests.

III. Results and Discussion

Data was collected for each test and post-processed to find the heat exchange, power consumption, capacity, and COP. The following sections outline the results of each test.

A. Peak Cooling Capacity Test

The peak cooling capacity test applied the maximum cooling load the piles may provide. The maximum and minimum outdoor ambient air temperatures were 30.9^{o}C and 16.4^{o}C, respectively. An averaged difference in temperature of 19.58^{o}C across the pile's inlet and outlet was found as presented in Fig. 3.

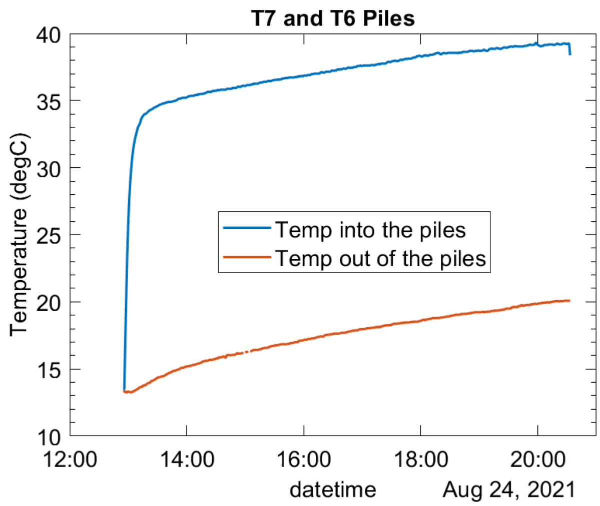

Figure 3. The temperature of the water entering and leaving the piles during the peak cooling capacity test.

As shown above, the temperature of the water going into the piles increases significantly at the start of the test in response to the transient operation of the heat pump. It then steadily increases for the remainder of the test. Both the inlet and outlet pile temperatures increase with a similar trend over the duration of the test.

Upon analyzing the temperatures of all eight piles, it was observed that the pile outlet temperatures increased from approximately 13.9ºC to 20.5ºC over the duration of the test. This is shown in Fig. 4 below. The curves confirm a similar trend for each pile indicating their performance is as expected and any variation between the piles is negligible.

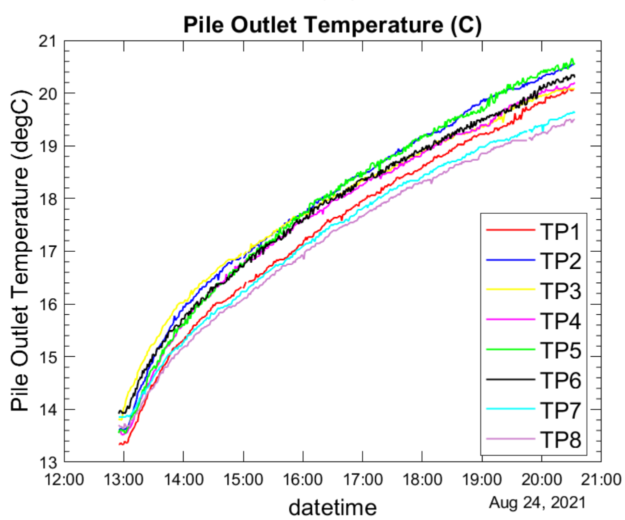

Figure 4. Outlet temperature for each pile during the peak cooling capacity test.

Table I shows the averaged results of the critical performance metrics for the test for the pile array. The COP of the heat pump was 2.13. Given the large difference in temperature in Fig. 3, the COP was expected to be higher, however, this may be explained by the limitations created by having a heat exchanger present and possible losses experienced in the system.

TABLE I. PEAK COOLING CAPACITY TEST AVERAGED DATA

Variables	**Averaged Data**
Flow Rate (m^3/s)	9.16E-4
Heat Exchange (kW)	13.24
Power Consumption (kW)	5.71
Capacity (tons)	3.46
ΔT (ºC)	19.58
COP of the System	2.13

B. *Cooling Steady State Capacity Test*

Ten tests were conducted to determine the steady state performance of the piles at various flow rates going through the heat exchanger on the heat pump side. As expected, as the flow rate through the heat exchanger increased, the temperature difference between the inlet and outlet of the piles increased. The averaged data for each test can be seen in Table II below. The COP ranges from 3.2 to 4.5.

TABLE II. COOLING STEADY STATE CAPACITY TEST AVERAGED DATA

Test Number	**Averaged Data**				
	Flow Rate (m^3/s)	*ΔT (ºC)*	*Capacity (Tons)*	*Power Consumption (kW)*	*COP of the System*
1	1.26E-5	0	0.1	0.1	4.5
2	1.32E-5	0	0.13	0.13	4.3
3	3.15E-5	0	0.17	0.15	4.8
4	5.11E-5	0.4	0.2	0.18	3.8
5	6.31E-5	3.1	0.4	0.37	4
6	3.79E-4	7	2	1.7	4.2
7	5.17E-4	7.2	2.5	2.3	4.2
8	5.99E-4	8	3	2.5	4.4
9	8.33E-4	17.5	3.1	4.2	3.2
10	8.86E-4	14.8	2.88	3.1	3.22

It should be noted that the 3-way electronically activated valve exhibits a non-linear relationship between its voltage setting (ranging from 0 V to 10 V, allowing increments of 0.1 V) and the flow rate to the heat exchanger.

C. *Heating Steady State Capacity Tests*

The steady state heating capacity was found at three flow rates. The maximum and minimum ambient outdoor temperature for these tests is 2.57ºC and -4.93ºC, respectively. The test in Fig. 5 incorporated a flowrate through the heat exchanger of 4.61E-5 m^3/s (0.73 GPM). The figure shows that the pile inlet temperature dropped quickly at test initiation when the flow through the heat exchanger was increased. The inlet and outlet temperatures continued to slowly decrease until the completion of the test.

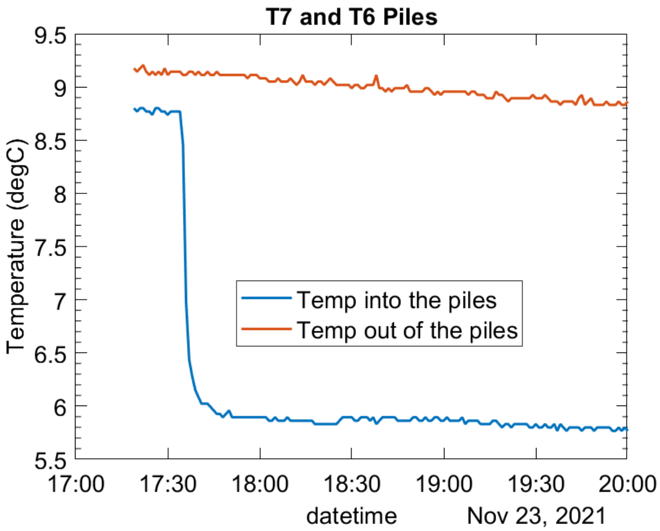

Figure 5. The temperature of the water entering and leaving the piles during the 4.61E-5 m^3/s heating steady state capacity test.

Once the flowrate was increased to 1.02E-4 m^3/s (1.61 GPM) in test 2, a larger difference in temperature was seen between the inlet and outlet of the piles. These two values presented in Fig. 6 show a similar trend to test 1 as they continued to decrease over the duration of the test. The slope of the graphs in the steady state region is relatively small indicating the heat pump is maintaining operation at its maximum speed.

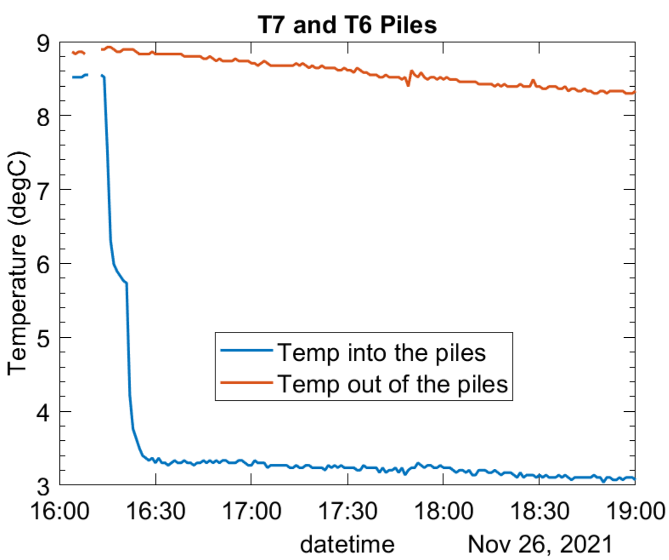

Figure 6. The temperature of the water entering and leaving the piles during the 1.02E-4 m^3/s heating steady state capacity test.

The third test, shown in Fig. 7, used a flow rate of 1.46E-4 m^3/s, resulting in a slightly larger temperature difference of 5.50°C compared to the temperature difference for tests 1 and 2 of 2.82°C and 4.87°C, respectively. The piles produced similar trends in all three tests, performing as expected.

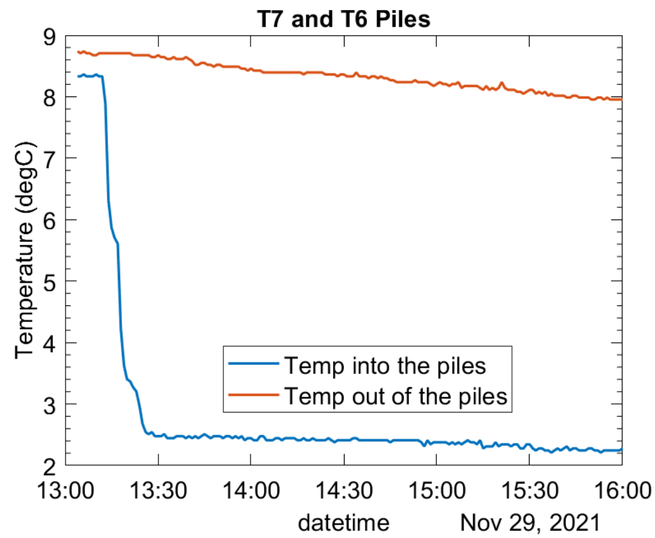

Figure 7. The temperature of the water entering and leaving the piles during the 1.46E-4 m^3/s heating steady state capacity test.

Table III below shows the averaged data for the heating steady state capacity tests. The averaged COP for all three tests is 3.35. As expected, as the flow rate increased, the difference in temperature increased.

TABLE III. TABLE TYPE STYLES

Test Number	Averaged Data				
	Flow Rate (m^3/s)	*ΔT (°C)*	*Capacity (Tons)*	*Power Consumption (kW)*	*COP of the System*
1	4.61E-5	2.82	0.34	0.34	3.48
2	1.02E-4	4.87	0.87	0.92	3.28
3	1.46E-4	5.50	1.91	1.16	3.30

These heating steady state capacity tests also serve as a foundation for future heating tests, allowing the authors to determine an appropriate set point and operating conditions to achieve steady state operation from the heat pump in heating conditions. This will ensure future test data is collected effectively.

D. Testing Limitations

The heat exchanger and choice of fluid in the pile array placed some limitations on testing, resulting in further heating steady state and peak capacity tests being unfeasible. Water was chosen as the working fluid in the pile array due to the concern of possible leaks in a yet-untested technology, and for cost considerations. With winter temperatures well below 0°C, heating testing runs the risk of freezing the water in the pile loop, potentially damaging the heat exchanger. It was determined through testing that flowrates through the heat exchanger above 1.46E-4 m^3/s (2.32 GPM) will result in the water reaching temperatures below 0°C.

Analyzing the difference in temperature across the piles, ΔTs of over 15°C can be seen from the piles. The authors speculate that the piles have potential to perform at higher efficiencies and COPs based on the temperature difference across the piles but are currently limited by the heat exchanger. Future work will include simulating a mutli-pile system without the heat exchanger to determine the performance of the piles when directly connected to the heat pump.

IV. Summary and Conclusion

Conventional geothermal systems comprising vertical or horizontal borehole loops have not seen maximal implementation due to their long payback period, high initial costs, and lesser return on investment. Helical steel piles offer an effective dual-use solution as an in-ground heat exchanger and structural support, to significantly decrease installation cost and space requirements. A design for the piles has been developed and an experimental site with eight piles has been installed in Waterloo, Ontario. Cooling and heating tests have been conducted to determine the peak and steady state capacity of the system.

The peak cooling capacity test presented a difference in temperature across the piles of 19.5^{o}C. This resulted in a peak cooling COP of 2.13. For steady state operation analyzed at various flow rates, the results showed, as the flow rate was increased, the change in temperature also increased. When the full steady state cooling load was placed on the piles, a change in temperature of 14.8^{o}C and a COP of 3.4 was found. In the heating season, the steady state capacity was evaluated at various flow rates. For a flow rate of 1.46E-4 m^3/s, a change in temperature of 5.50^{o}C was found with a COP of 3.30. The flow rate directed to the heat exchanger during heating season tests is limited by the temperature of the fluid circulating in the piles. Since the circulating fluid in the piles is water, reaching a temperature below 0^{o}C will risk the water freezing which can potentially damage the heat exchanger. Future work intends to model the pile array without the heat exchanger to further evaluate the heating capacity of the system and understand the effects of directly connecting the piles to the heat pump.

Overall, structural piles have the potential to make geothermal energy widely accessible to both the residential and commercial building industries in Canada. The results presented in this paper demonstrate their ability to produce large differences in temperature which result in high efficiencies and COPs. Future work includes continuing heating testing to further the understanding of the pile performance under a heating load, and expanding the initial model created to a multi-pile model to evaluate system performance without a heat exchanger.

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