COMPARISON OF U-TUBE BOREHOLES AND A THERMOSIPHON ON HEAT PUMP PERFORMANCE IN AN AQUIFER

by

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STATEMENT OF THESIS APPROVAL

The thesis of ____

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ABSTRACT

Reducing our energy consumption and dependence on fossil fuels has become a common social, political and engineering goal. Heating and cooling of buildings account for a large percentage of the energy consumption in the United States. Improving HVAC efficiency in buildings can play a major role in reducing energy use.

Small scale geothermal systems that utilize low-grade heat have gained popularity as a way to reduce HVAC energy consumption. U-tubes and thermosiphons are two different technologies designed to transfer heat to and from the ground in order to provide building heating and cooling.

This thesis presents a short and long term experimental analysis. The short term analysis compares the performance of these technologies. The long term analysis focuses on the U-tubes, looking at the COP of the overall system during the course of a heating season and comparing temperatures for a theoretical air source heat pump system.

CONTENTS

CHAPTERS

LIST OF FIGURES

NOMENCLATURE

COP	coefficient of performance
$COP_{HP,rev}$	reversible COP of a heat pump, $COP_{HP,rev} = \frac{T_H}{T_H - T_L}$
T_H	temperature of the high-temperature reservoir
T_L	temperature of the low-temperature reservoir
$\dot{Q}_L$	the rate of heat absorbed by the heat pump from the geothermal system
$\dot{m}$	the mass flow rate of the glycol mixture
c_p	specific heat of the glycol mixture
ΔT	the temperature difference of the glycol mixture between the heat pump inlet and outlet
$\dot{V}$	the volumetric flow rate of the glycol mixture
ρ	the density of the glycol mixture
$\dot{Q}_{L,normalized}$	the rate of heat absorbed by the heat pump from the geothermal system per unit length of borehole, $\dot{Q}_{L,normalized} = \frac{\dot{Q}_L}{Total\ Borehole\ Length}$
COP_{HP}	coefficient of performance of any heat pump, $COP_{HP} = \frac{Q_H}{W_{net}}$
Q_H	the amount of heat rejected from the heat pump
W_{net}	the electrical work input to the heat pump
Q_L	the amount of heat absorbed by the heat pump from the geothermal system
$\dot{W}_{net}$	the rate of electrical work input to the heat pump

CHAPTER 1

INTRODUCTION

1.1 Project Background

This experiment was part of a whole house energy monitoring project. The project was a joint effort between the University of Utah Mechanical Engineering Department and ConSol. It was funded by a grant from Building America, a branch of the Department of Energy. The goal of the project to quantify the energy savings from a variety of new, 'green' technologies in the residential construction industry. These technologies were implemented in a new housing development in Park City, UT. The system of particular interest for this study was the ground source heat pump system which utilized vertical U-tubes as the ground loop heat exchanger. Another type of ground heat exchanger called a thermosiphon was integrated into the heat pump system so that it could be compared to the U-tube system. English units are used throughout this document due to the requirements of these other parties.

1.2 Motivation

Reducing our energy consumption and dependence on fossil fuels has become a common social, political and engineering goal. Motivations for this goal range from concerns about anthropogenic climate change to improving air quality to reducing energy costs to decreasing dependence on foreign energy sources. Growing energy demands and increasing concerns about the environmental impact of generating energy from fossil fuels continue to drive the pursuit of clean, carbon free energy generation on the production side and increasing efficiency on the demand side. According to DR International (2009), buildings consumed 39% of the U.S. primary energy in 2006. Therefore improved efficiency in this area can play a major role in reducing energy use. No matter the motivation, reducing the energy consumption of buildings is one of the best ways to achieve these goals. One of the systems that is growing increasingly popular to reduce building energy usage is the Ground Source Heat Pump (GSHP) system. Another emerging technology is the thermosiphon. The motivation for this thesis is to better understand the characteristics of these systems in order to better integrate them into building designs and further refine sizing procedures. This improved understanding will help to further refine system sizing and design techniques so that energy efficiency can be improved.

1.3 Novelty

The majority of research on GSHP systems has been focused on mathematical models simulating the subsurface heat transfer occurring. There has been little experimental verification of the simulation results from these mathematical models. The novelty of this experiment is that while there have been thousands of GSHP installations around the world (Florides and Kalogirou, 2007), there have been very little experimental data gathered on these systems. One of the only documented experiments was conducted in China on a large cylindrical piling that had U-tubes and instrumentation installed (Nam et al., 2008).

1.4 Hypotheses

The major design flaw with U-tube boreholes is the close proximity of the inlet fluid pipe to outlet fluid pipe within the borehole (Figure 1.1.) This configuration dramatically reduces the heat transfer potential of the system because the fluid on its way down the borehole is not only influenced by the temperature of the surrounding soil, but also by the temperature of the fluid in heading back up the opposite side of the U-tube. The thermosiphon transfers heat based on a phase change in a single pipe. The hypothesis is that the thermosiphon will yield higher heat transfer rates per foot of drilling because it will not suffer from the “cancellation” of the GSHP system.

COP, coefficient of performance, is a term used to quantify of the efficiency of a heat pump system. The thermodynamic definition of the reversible COP of a

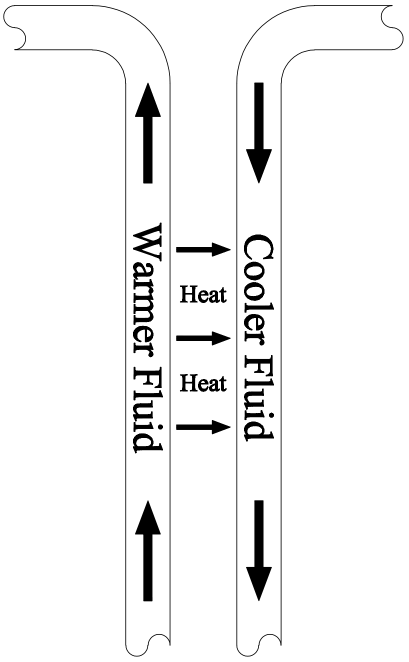


Figure 1.1: Interfering Heat Transfer in U-tubes. When the cool fluid enters the U-tube it not only extracts heat from the surrounding grout and soil, but also from the warmer fluid exiting the other side of the U-tube. Extracting heat from the warmer, exiting side of the U-tube lowers the exiting fluid temperature which decreases the effectiveness of U-tube as a heat exchanger.

heat pump is, $COP_{HP,rev} = \frac{T_H}{T_H - T_L}$. As heat is removed from the ground during the heating season, it is predicted that the ground temperature, T_L, will decrease, causing the COP to decrease. The energy monitoring equipment on this system allows for the actual measurement of these temperature changes, not just predicted based on a mathematical model.

1.5 Ground Source Heat Pumps

1.5.1 Description

GSHP systems couple a heat pump to an in ground heat exchanger in order to exploit the relatively constant soil temperatures that occur underground below a depth of about 5 meters (Florides and Kalogirou, 2007). The idea is that the ground temperature is thermodynamically favorable to the ambient air temperature, leading to a higher COP. In many geographic locations, this constant temperature is a more favorable thermal energy source for heating than air if the air temperature is cooler and for cooling if the air is warmer (Omer, 2008). A diagram explaining the operating principle of a vertical U-tube heat exchanger can be seen in Figure 1.2.

There are four major components in a GSHP system. The first component is a subterranean heat exchanger, which is typically a closed loop network of high-density polyethylene pipe. The piping network filled with a working fluid, typically a mixture of water with ethylene glycol or methanol. The second component is a heat pump, which uses a refrigeration cycle, to supplement the heating or cooling from the subterranean heat exchanger. The third component is an inline pump to circulate the working fluid between the subterranean heat exchanger and the heat pump. The fourth component is a system to distribute the intended space conditioning, which could be a forced air or radiant heating system.

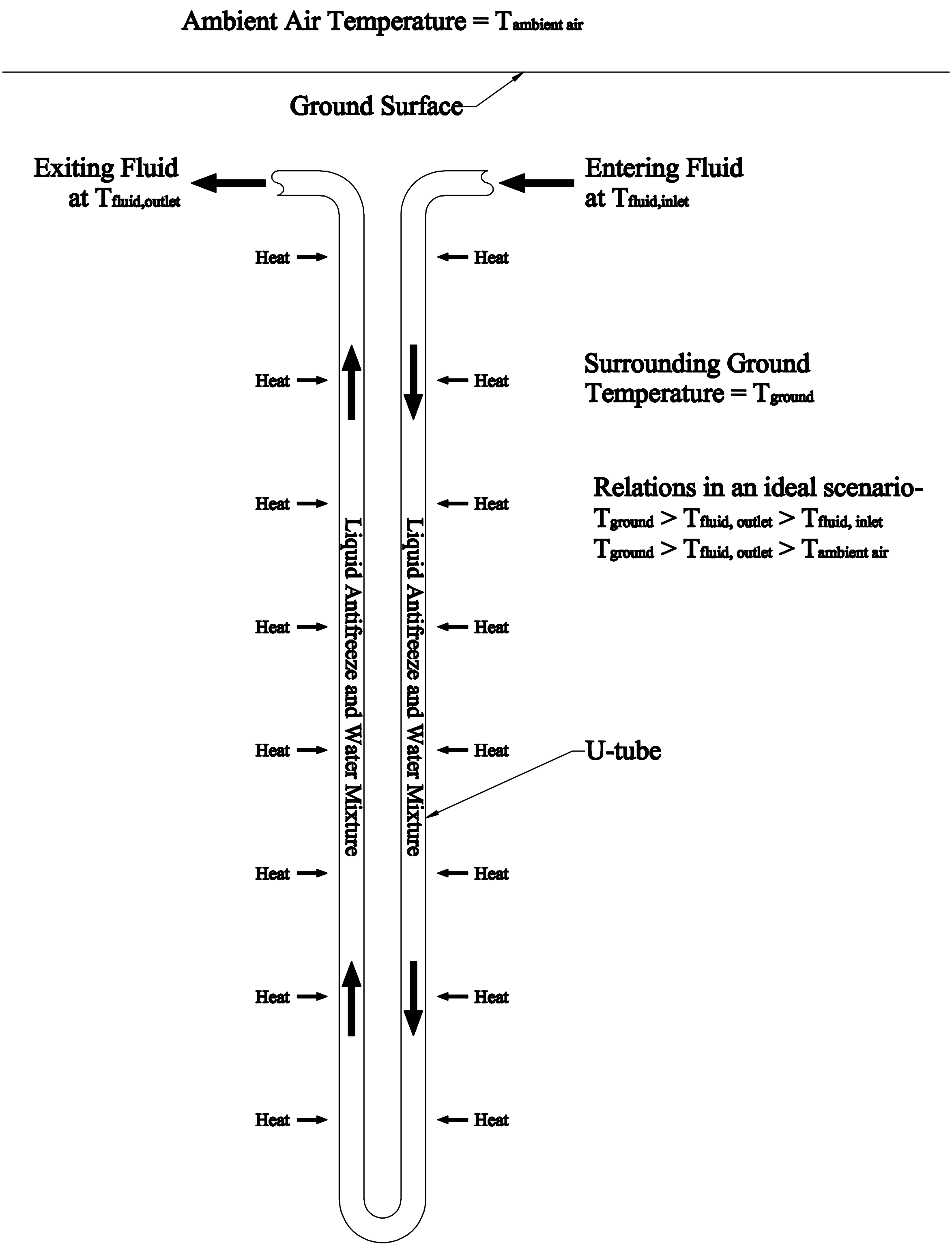
1.5.2 Types

There are many different types of GSHP systems. The two most general categories are open and closed loop systems, each having their own advantages and disadvantages. Open systems could consist of air passing through tubes buried in the ground or water injection/recovery wells. Closed systems consist of horizontal or vertical networks of piping buried underground (Florides and Kalogirou, 2007; Omer, 2008; Rawlings and Sykulski, 1999). There is not one best type of GSHP system, design choices are made based on site, budget, and installation factors.

1.5.3 Advantages

GSHPs are a more mature technology than thermosiphons. This maturity is the greatest advantage of GSHPs compared to thermosiphons. Well established installation procedures, design parameters and materials/tools specific to building these systems already exist. All of these factors result in more durable, easier to design systems.

Figure 1.2: U-tube Operating Principle. The U-tube extracts heat from the ground by using a long pipe as a heat exchanger in the ground. A fluid, cooler than the ground enters the U-tube. As it travels the length of the U-tube, it extracts heat from the warmer ground and exits the U-tube at a warmer temperature than when it entered.


Ambient Air Temperature = $T_{\text{ambient air}}$
Ground Surface
Exiting Fluid at $T_{\text{fluid,outlet}}$
Entering Fluid at $T_{\text{fluid,inlet}}$
Heat
Surrounding Ground Temperature = T_{ground}
Relations in an ideal scenario-
$T_{\text{ground}} > T_{\text{fluid, outlet}} > T_{\text{fluid, inlet}}$
$T_{\text{ground}} > T_{\text{fluid, outlet}} > T_{\text{ambient air}}$
Liquid Antifreeze and Water Mixture
Liquid Antifreeze and Water Mixture
U-tube

1.5.4 Disadvantages

The inline pump and heat pump increase the initial capital investment and operating cost compared to a passive technology where this equipment is not necessary, such as thermosiphons. The other primary disadvantage of closed loop GSHPs is that it is very difficult to design a system where the inlet and outlet flows of the system do not thermally interfere with one another. Figure 1.1 shows the performance robbing heat transfer that occurs in the U-tube borehole.

1.5.5 Current Research

There has been a substantial amount of research involving GSHPs in recent years. Most of the current research has been focused on numerical models of the underground heat transfer (Nam et al., 2008; Yavuzturk et al., 1999). Short term behavior modeling is important in order to determine system energy consumption on a given day or on an hour-by-hour basis (Yavuzturk and Spitler, 1999; Xu and Spitler, 2006). Long term models are important because they evaluate the effect of heat rejection and extraction on ground temperature over the period of years, in order to mitigate thermal saturation of the surrounding ground, while with the goal of minimizing the system borehole length for cost control (Nam et al., 2008; Yavuzturk et al., 1999). This is by no means the full extent of the published modeling research, but represents the general direction of current research in this area.

Another pertinant research area in GSHPs has been borehole thermal conductivity testing. In-situ thermal conductivity is one of the most important design parameters, but also the most difficult to ascertain. This research is particularly relevant because thermal conductivity for this experimental site was abnormally high as a result of ground water flow. This artificially high, measured, thermal conductivity does not represent the actual value, but is inflated due to advection. This measured value of thermal conductivity only represents an apparent thermal conductivity, which will affect system performance for better or worse, according to Chiasson et al. (2000).

To the author's knowledge, the major hole in low grade geothermal research is the lack of experimental data. The novelty of this experiment is that it gives greater insight into the underground heat transfer. Better understanding of the underground formation temperature response to heat extraction will refine sizing practices, resulting in reduced initial capital and operating costs for GSHP systems.

1.6 Thermosiphon

1.6.1 Description

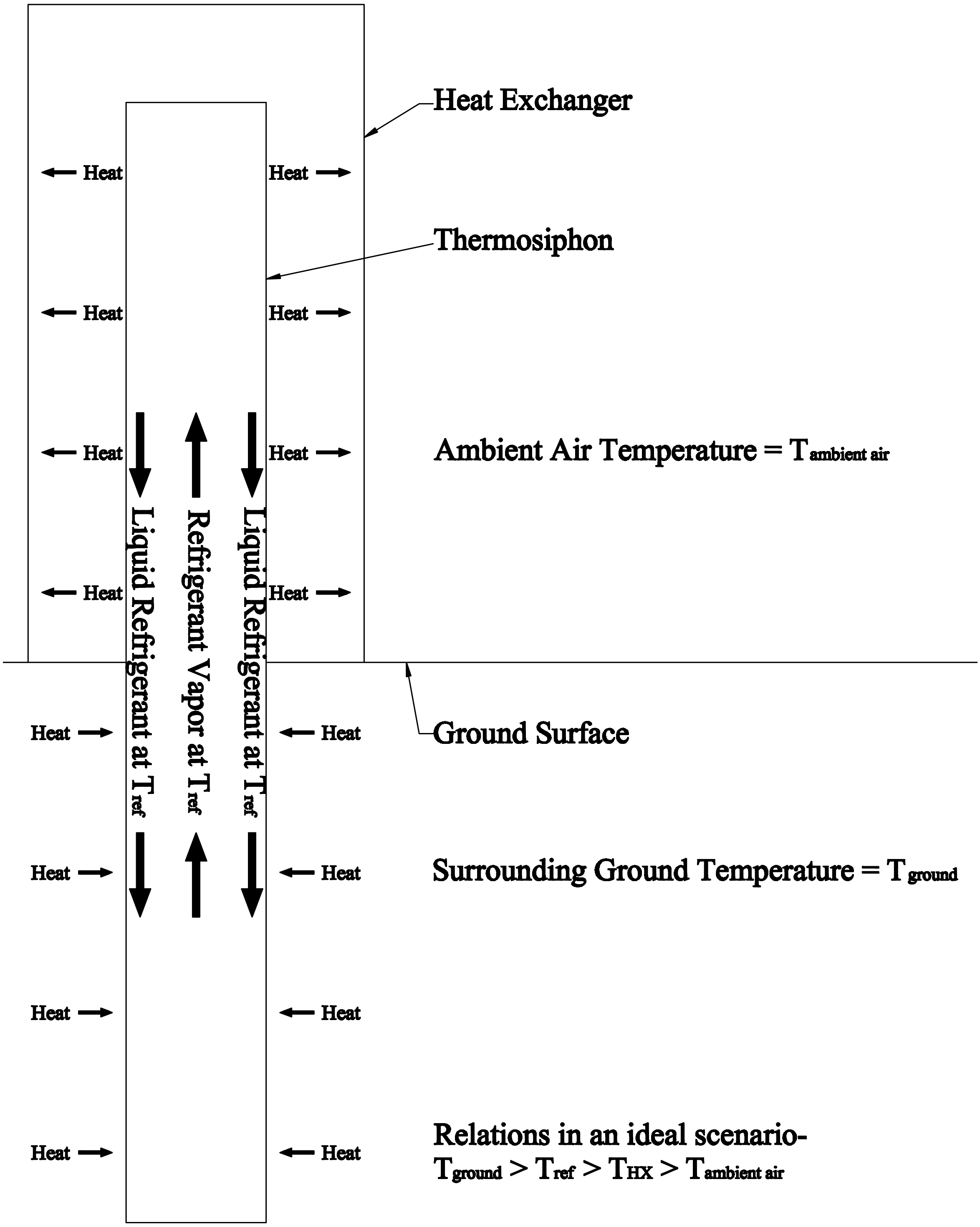
A thermosiphon is a superconducting device that transfers heat with a theoretical temperature difference of zero. A thermosiphon is a pipe that is evacuated and charged with a refrigerant. When it is positioned at a slope, with a heat source on the bottom and a heat sink at the top, the thermosiphon begins to function as a superconductor. The heat source at the bottom induces vaporization of collected liquid, the density difference of this vapor to the surrounding liquid causes it to rise in the pipe, until it reaches the heat sink at the top of the tube. The heat sink induces condensation, the resulting liquid is now denser than the surrounding vapor causing it to sink in the tube, returning to the bottom of the tube for the cycle to repeat. A diagram of the thermosiphon operating principle can be seen in Figure 1.3.

1.6.2 Advantages

The biggest advantage of thermosiphons is that they passively extract heat from the ground in the configuration shown in Figure 1.3. There is no need for a pump to circulate the working fluid in order for heat transfer to occur in this application of thermosiphons.

Another advantage of the thermosiphon is a higher heat transfer rate per foot of drilling (Udell et al., 2011). The single pipe design of a thermosiphon means that it is not susceptible to the inefficient, cancellation that occurs in U-tube boreholes. It also has as an extremely high apparent thermal conductivity, due to the phase change nature of the design (Dunn and Reay, 1994).

Figure 1.3: Thermosiphon Operating Principle. Thermosiphon operation is driven by a phase change process. As heat moves from the warm ground to the cool air reservoir, liquid refrigerant in the bottom thermosiphon, the refrigerant undergoes a phase change, vaporization, and is converted from a liquid to a vapor. Once refrigerant starts to vaporize it becomes less dense than the surrounding liquid, causing it to rise. As it rises to the top of the thermosiphon, heat is extracted from the top of the thermosiphon to the cooler heat exchanger. This loss of heat caused the refrigerant to undergo a phase change, condensation, and is converted from a vapor to a liquid. The liquid, now denser than surrounding vapor, falls back down the walls of the thermosiphon to repeat the process.


Heat Exchanger
Heat
Thermosiphon
Ambient Air Temperature = $T_{ambient\ air}$
Liquid Refrigerant at T_{ref}
Refrigerant Vapor at T_{ref}
Liquid Refrigerant at T_{ref}
Ground Surface
Surrounding Ground Temperature = T_{ground}
Relations in an ideal scenario-
$T_{ground} > T_{ref} > T_{HX} > T_{ambient\ air}$

1.6.3 Disadvantages

The immaturity of thermosiphons in HVAC applications makes installation much more challenging. There are no established installation procedures or materials. There are no contractors who are experienced in installing these systems. All of these factors increase the potential for issues with proper installation, durability and serviceability which ultimately means unforeseen expense of the system.

The other disadvantage of the thermosiphon is that this passive extraction configuration is limited to heating applications.

The thermosiphon is essentially a pipe filled with a gas that is above atmospheric pressure. This means that the thermosiphon poses a slight danger because it is a form of pressure vessel.

If there is a small leak a thermosiphon system is more susceptible to stop functioning than a GSHP system, because the refrigerant vapor can escape very quickly causing a pressure drop. This creates a challenge because it demands an absolutely leak proof system for operation.

1.6.4 Current Research

One of the most publicized applications of thermosiphons was the trans-Alaska oil pipeline. The pipeline uses heat pipes in the supports in order to prevent melting of the permafrost (Dunn and Reay, 1994).

Heat pipes have been used by Japanese researchers to extract geothermal heat for snow melting applications (Tanaka et al., 1982). This snow melt application has had moderate success.

A more recent application of the thermosiphon is thermal energy storage. This application is being studied by Dr. Kent Udell's laboratory at the University of Utah. The concept is to use thermosiphons arrays in the ground as a means of passive energy storage in the winter, in order to utilize this resource as a means for ultra-high efficiency air conditioning during the summer months (Udell et al., 2011, 2009).

CHAPTER 2

METHODS

2.1 Testing Methodology

The system testing consisted of a short term comparison of the U-tube system to the thermosiphon system then a long term analysis of the U-tube system.

2.1.1 Short Term Comparison

The goal for the short term comparison was to run both the U-tube and thermosiphon systems each for at least 3 hours continuously during the same day in order to get an experimental performance comparison for the two systems in winter heating mode. This GSHP system does not typically run continuously for longer than 15 to 20 minutes while maintaining a constant interior set-point temperature during typical operation. The reasoning for running the system continuously for such a long period of time is that it takes roughly 30 minutes for the thermocouple readings to stabilize, in order to make meaningful relations. To get the heat pump system to run continuously, it was prevented from reaching its set-point temperature by opening the windows in the room where the thermostat is located and setting the desired room temperature well above the outside air temperature. It was not possible to run both the U-tube and the thermosiphon system at the same time. The U-tube system was tested first, then the thermosiphon system was tested, each for over 3 hours on November 22nd, 2010.

2.1.2 Long Term U-tube Analysis

A long term analysis was carried out on the U-tube system throughout the majority of the winter heating season. The focus was to determine temperatures along the length of the U-tube and GSHP *COP* trends throughout the heating season.

2.1.3 Energy Balance

The goal of measuring temperatures, Q_L and COP for both a U-tube and a thermosiphon system required sensors for measuring temperature, flow and power, along with integrating a thermosiphon into a U-tube GSHP system. A diagram of the experimental system lay-out is shown in Figure 2.1 and more detailed explanation of the systems can be found in the following sections.

The purpose of all the monitoring equipment installed is to be able to perform an energy balance on the system. This required temperature, flow rate and power measurements. Thermocouples were used to measure temperature. Turbine flow meters were used to measure the flow rate. WattNodes and Current Transformers were used to measure the electrical power consumption to find the work input to the heat pump and fluid pump.

2.1.3.1 Thermocouples

T-type thermocouples were used for measuring system temperatures. They were the cheapest, easiest to wire solution. Unlike some other temperature sensors, they do not require power to take a measurement. Unfortunately, thermocouples sacrifice the precision of other technologies, like thermistors. All of the thermocouples in this experiment were mounted on the outside diameter of the pipe, except for the heat pump inlet and outlet thermocouples in the first floor mechanical room which were immersed thermocouples (Figure 2.2.)

2.1.3.2 Flowmeter

Figure 2.3 shows the turbine based flowmeter used to measure the glycol flow rate which outputs a hall pulse.

Figure 2.1: Schematic Drawing of the Overall Experimental Set-up. This is a schematic drawing of the overall experimental set-up including the mechanical components and the monitoring equipment. Thermocouples are indicated by black dots with magenta text. The thermocouples are mounted on the outer diameter of the associated pipe unless indicated as, ‘immersed.’ Physical locations of equipment are indicated by the dash/dot lines and blue text.

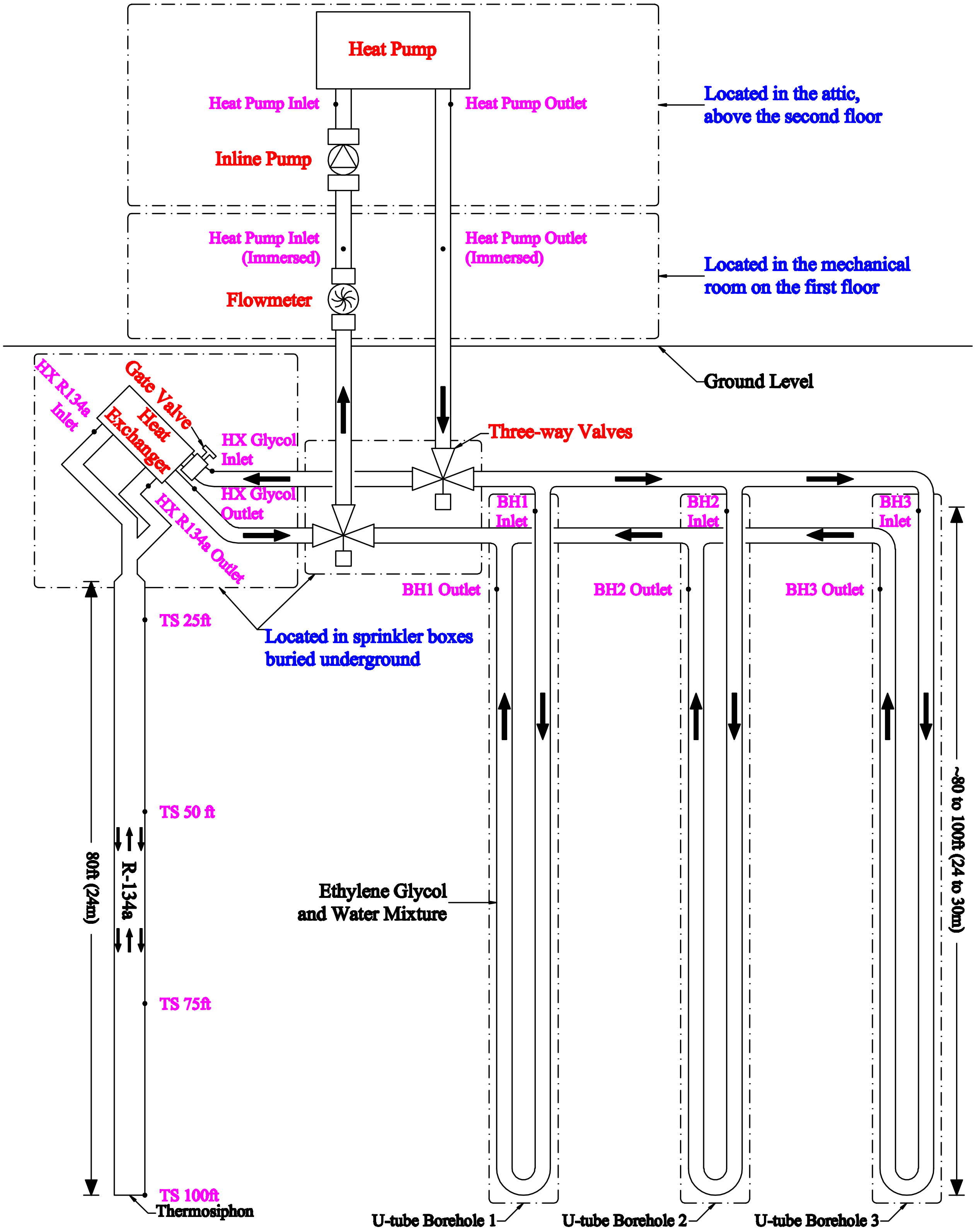

Heat Pump
Heat Pump Inlet
Heat Pump Outlet
Inline Pump
Located in the attic, above the second floor
Heat Pump Inlet (Immersed)
Heat Pump Outlet (Immersed)
Flowmeter
Located in the mechanical room on the first floor
Ground Level
HX R134a Inlet
Gate Valve
Heat Exchanger
HX Glycol Inlet
HX Glycol Outlet
HX R134a Outlet
Three-way Valves
BH1 Inlet
BH2 Inlet
BH3 Inlet
BH1 Outlet
BH2 Outlet
BH3 Outlet
Located in sprinkler boxes buried underground
TS 25ft
TS 50 ft
R-134a
80ft (24m)
TS 75ft
TS 100ft
Thermosiphon
Ethylene Glycol and Water Mixture
~80 to 100ft (24 to 30m)
U-tube Borehole 1
U-tube Borehole 2
U-tube Borehole 3

Figure 2.2: Immersed Thermocouples. Immersed thermocouples installed in the first floor mechanical room

Figure 2.3: Flowmeter. The flowmeter installed in the first floor mechanical room

2.1.3.3 Powermeter

The powermeter configuration consisted of a 50 amp Current Transformer, (CTs) on one leg of the two-phase power and a Continental Controls WNA-3Y-208-P WattNode. Pictures of these components installed in the main breaker panel for the building are shown in Figures 2.4, 2.5 and 2.6.

2.1.3.4 Data Logger

The data logger used to collect and store data from the sensors was a Campbell Scientific CR1000. Figure 2.7 shows the unit installed in its enclosure with all of the associated sensor wiring.

2.2 Design

2.2.1 Thermosiphon System

The goals for the thermosiphon system were to maximize heat extraction rates and to integrate it into the GSHP system so that heat could be transferred to the heat pump.

2.2.1.1 Thermosiphon Boiling Enhancement

In order to maximize heat extraction rates, nucleation sites for boiling in the inside of the pipe had to be increased. The galvanized pipe was stuffed with a wire mesh and hardware cloth in order to achieve this result. The hardware cloth, fiberglass screen material, was intended to increase the pipe roughness, which provides more boiling sites, therefore increasing the heat transfer rate. The wire mesh was intended to create a frame inside the pipe which forced the hardware cloth to contact the inside surface of the pipe.

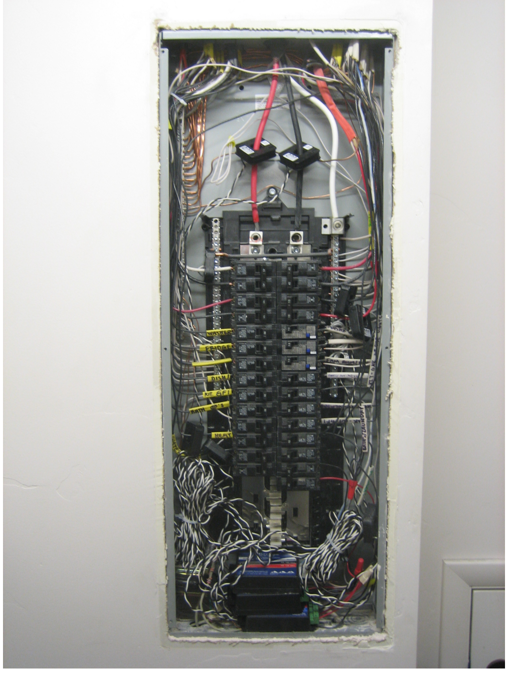


Figure 2.4: Powermeters. CTs installed just off of the panel and WattNodes stacked below the panel

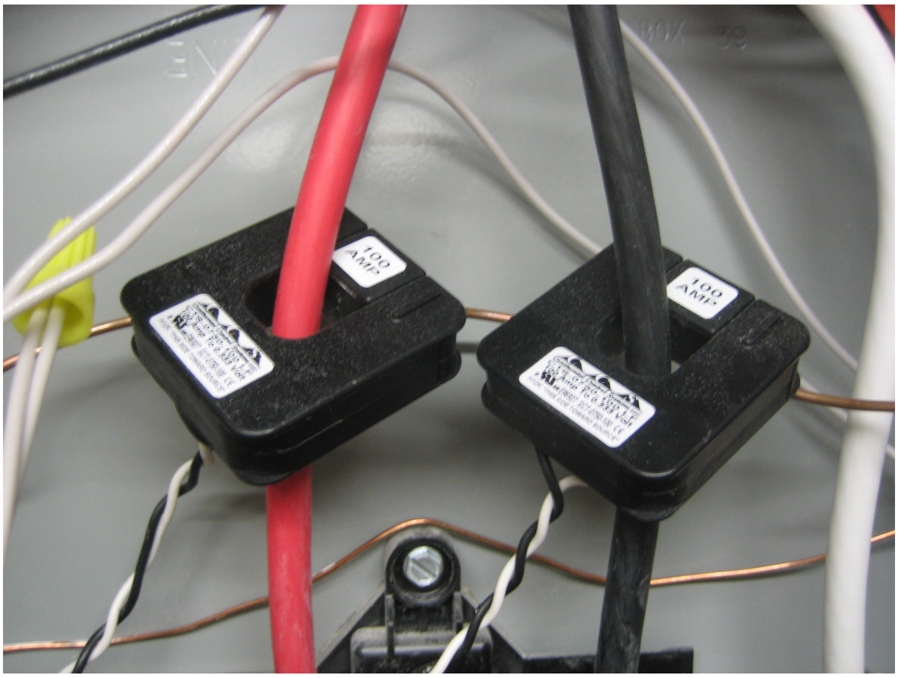


Figure 2.5: Current Transformers. Split-core CTs installed around the main power feed on the breaker panel.

Figure 2.6: WattNodes. WattNodes installed in the panel enclosure.

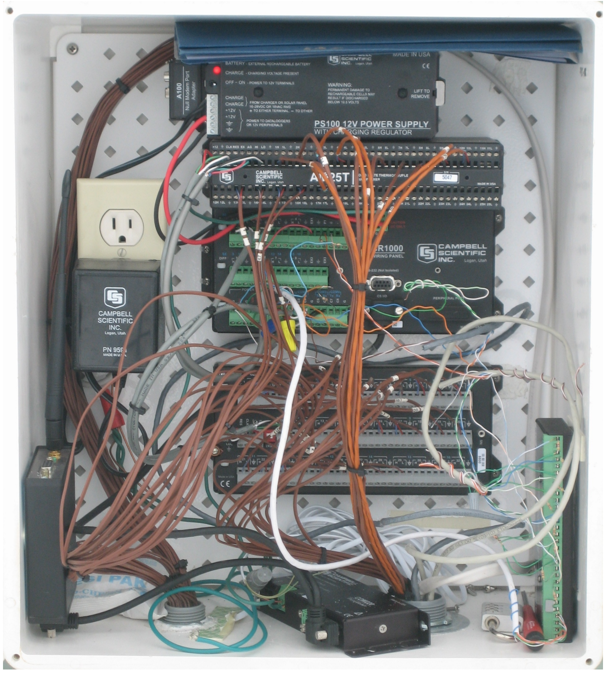


Figure 2.7: Data Logger. The data logger and enclosure installed on the exterior of the building.

2.2.1.2 Thermosiphon Heat Exchanger

A problem with integrating the thermosiphon into the GSHP system was the difference in working fluids. In order to solve this problem, a shell and tube heat exchanger was used to transfer thermal energy between the refrigerant in the thermosiphon and the propylene glycol in the GSHP system. The heat exchanger was installed at an incline so that the condensing refrigerant drains out of the heat exchanger more effectively, returning to the thermosiphon (Figure 2.8.) The heat exchanger was enclosed with a sprinkler box, so that it was still accessible once the surrounding dirt was backfilled (Figure 2.9.)

2.2.1.3 Three-way Valves

The other challenge with integrating the thermosiphon into the GSHP system was diverting the glycol fluid flow. In order to gather meaningful data, the loop from the heat pump must operate with both the thermosiphon and U-tube system independently. This was accomplished by installing a three-way diverting ball valve in both the supply and return propylene glycol lines (Figure 2.10.) A plastic drum was used to create an enclosure around the valves so that they had some protection once they were buried (Figure 2.11 and 2.12.) ABS pipes were installed directly over the valve adjustment handles so that the position of the valves could be changed once the valves were buried (Figure 2.13.)

2.2.2 Thermocouple Junctions

Due to the unplanned configuration of the drill rig, it was necessary to cut the thermocouples for the heavily monitored U-tube borehole and thermosiphon short of the data logger during their installation. The wires had to be cut at the top of the boreholes at the elevation of the horizontal tubing because it was not possible to route the full length of wire, necessary to reach the data logger, through the drill rig in a configuration that made it possible to remove the drill casing. It also would have been difficult to get a wire label to stick and survive the drill casing removal process, so the wires were cut without labels. Once the drill casing was removed the location of the wires along the length of the U-tube and thermosiphon

Figure 2.8: Thermosiphon Heat Exchanger. The heat exchanger was mounted at an incline on top of the thermosiphon to enhance draining of condensed refrigerant to the thermosiphon.

Figure 2.9: Sprinkler Box for H.X.. A sprinkler box providing access to thermosiphon heat exchanger and a thermocouple junction enclosure.

Figure 2.10: Three-way Valves. Three-way valves installed in the propylene glycol supply and return lines for the heat pump.

Figure 2.11: Heat Exchanger and Three-way Valve Enclosure. The three-way valve enclosure shown with the thermosiphon heat exchanger.

Figure 2.12: Valve Enclosure. Hardware cloth was stapled to the valve enclosure to keep soil and debris out after the enclosure was buried.

Figure 2.13: Valve Enclosure Access. A sprinkler box with ABS pipes providing access to three-way valves in the buried valve enclosure.

was deduced by measuring the resistance of each wire; the highest resistance wires were the longest, the lowest resistance wires being the shortest. At this point, the location of the each wire was known and the wire numbers were applied.

Unplanned thermocouple junctions had to be made underground at the top of the U-tube and the thermosiphon. This required a durable, watertight connection which could be buried and weatherized the connections. Enclosures were made out of 4-inch nominal diameter ABS pipe. The pipe was cut into approximately 6-inch lengths with caps fitted on each end. Holes were drilled in one of the caps, each hole being just large enough to pass one thermocouple wire through the cap (Figure 2.14). Once the wires were passed through the cap, they were stripped and standard electrical wire nuts were used to connect the corresponding wires (Figure 2.15). Epoxy was applied to the point where each wire penetrated the cap on both the inside and outside (Figure 2.16). Finally, the caps were ABS glued to the section of ABS pipe (Figure 2.17).

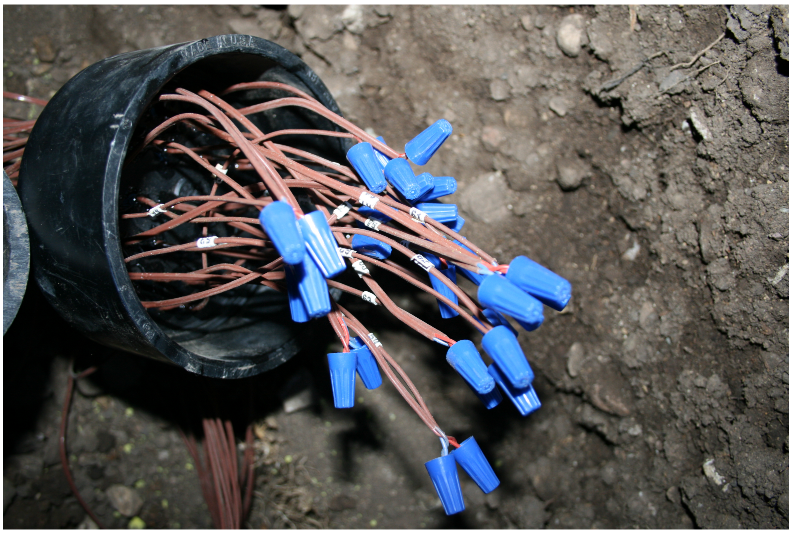


Figure 2.14: Thermocouple Enclosure: Step 1. Thermocouples after being routed though the ABS cap at one end and connected with wire nuts.

Figure 2.15: Thermocouple Enclosure: Step 2. The thermocouple junction enclosure with the section of ABS pipe attached, before the second cap is attached.

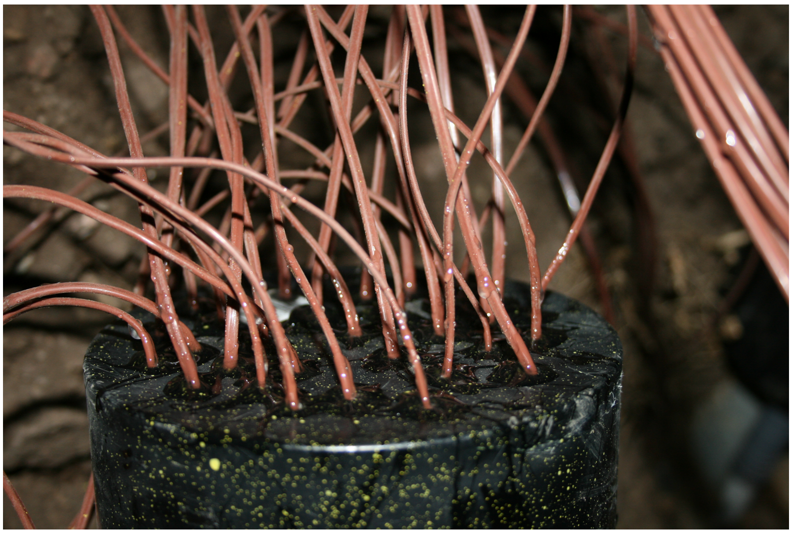


Figure 2.16: Thermocouple Enclosure: Step 3. The epoxy seals around where the thermocouple wires penetrate the ABS cap.

Figure 2.17: Thermocouple Enclosure: Final Product. The finished thermocouple junction enclosure.

2.3 Manufacturing

2.3.1 Thermosiphon

To construct the thermosiphon, first, the wire mesh and hardware cloth were cut to length and width (Figure 2.18). Second, the wire mesh was wrapped around the outside of the galvanized steel pipe it would eventually be installed in (Figure 2.19). This gave the wire mesh an initial cylindrical form. The wire mesh was then wrapped around a 1-inch diameter length of PVC pipe to give the wire mesh an even smaller diameter (Figure 2.20). The wire mesh was then laced into itself so that it formed a cylinder around the PVC pipe. Once the entire length of the wire mesh was laced into itself (Figure 2.21), the length of hardware cloth was wrapped around the wire mesh cylinder and the entire assembly was inserted into the galvanized steel pipe (Figure 2.22).

Four 20-foot lengths of 1.5-inch, nominal-diameter, galvanized steel pipe were built according to the proceeding procedure.

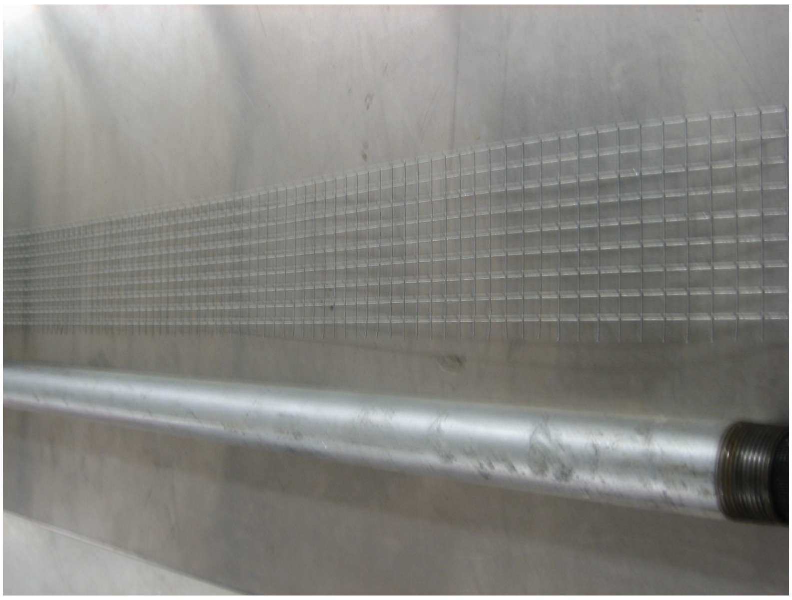


Figure 2.18: Thermosiphon Manufacturing: Step 1. Wire mesh cut to length and width.

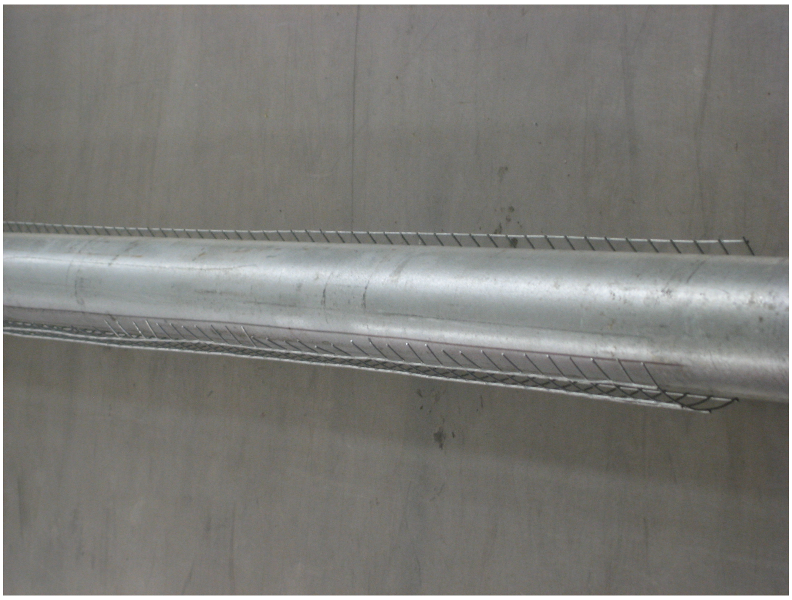


Figure 2.19: Thermosiphon Manufacturing: Step 2. Wire mesh taking form around the outside of the galvanized pipe it was eventually installed inside of.

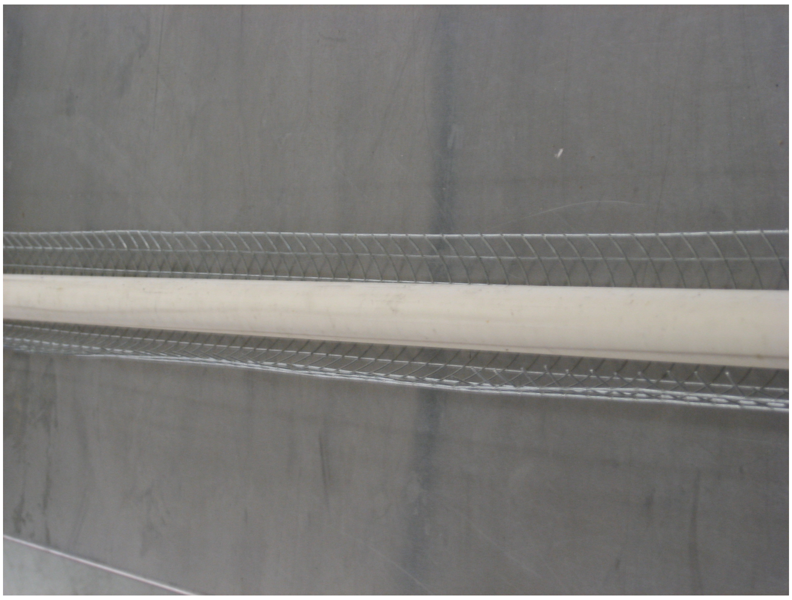


Figure 2.20: Thermosiphon Manufacturing: Step 3. The PVC pipe inside of the partially formed wire mesh cylinder.

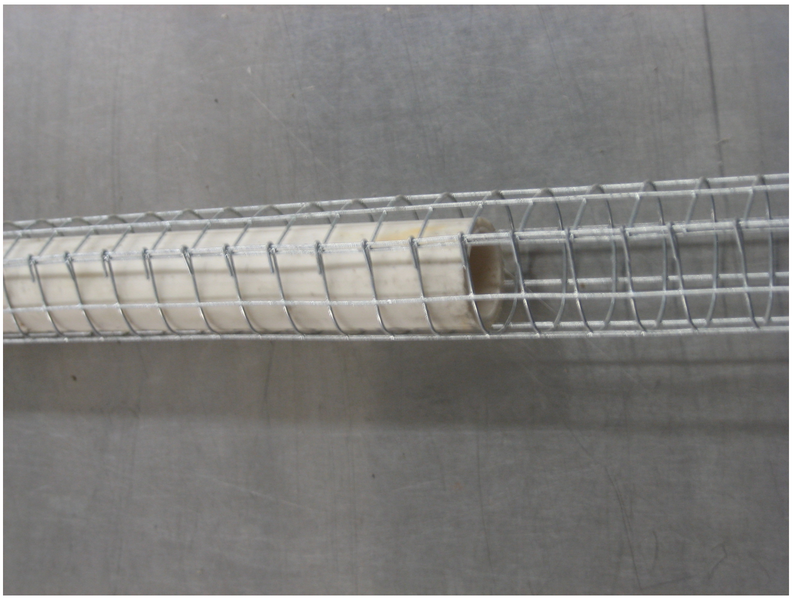


Figure 2.21: Thermosiphon Manufacturing: Step 4. The wire mesh cylinder once it has been formed.

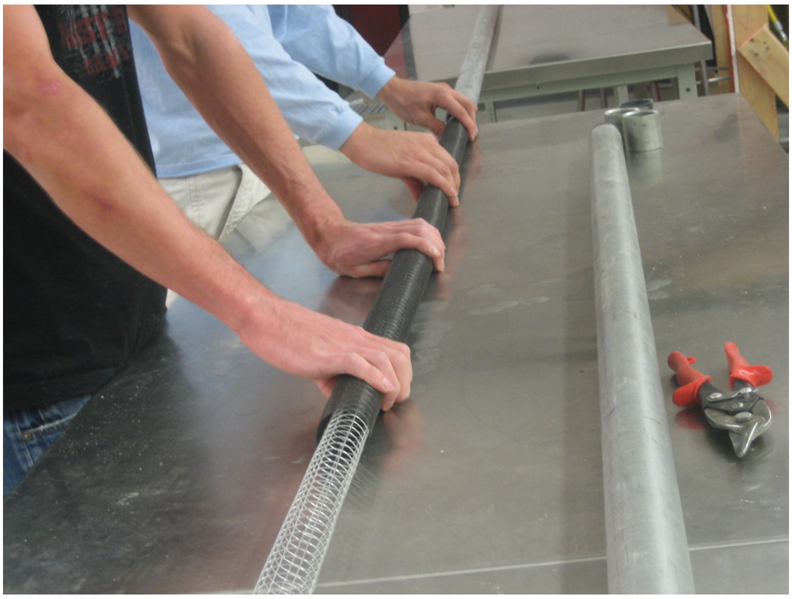


Figure 2.22: Thermosiphon Manufacturing: Step 5. The wire mesh and hardware cloth assembly being inserted into the galvanized steel pipe.

2.3.2 Thermocouples

Off the shelf, premanufactured thermocouples were not an option for this project because the long thermocouple lengths meant exorbitant cost. Instead, 1000-foot spools of thermocouple grade wire were purchased and the thermocouples were manufactured in-house. This procedure was as follows; a length of thermocouple wire was measured and cut (Figure 2.23), an approximately 1-inch length of the outer jacket was stripped (Figure 2.24), an approximately 1-inch length of the insulation was stripped from each of the individual wires (Figure 2.25), the entire exposed length of the two individual wires was twisted together (Figure 2.26) and the exposed portion of wire was covered in two to three coats of liquid tape to weatherize (Figure 2.27).

2.4 Installation

2.4.1 U-tube System

There were three U-tubes installed for the GSHP system. Each U-tube was between 80 and 100 feet long, generally shallow for a GSHP system, but deemed sufficient due to an abnormally high apparent conductivity value for the soil based

Figure 2.23: Thermocouple Manufacturing: Step 1. Thermocouple wire before the procedure.

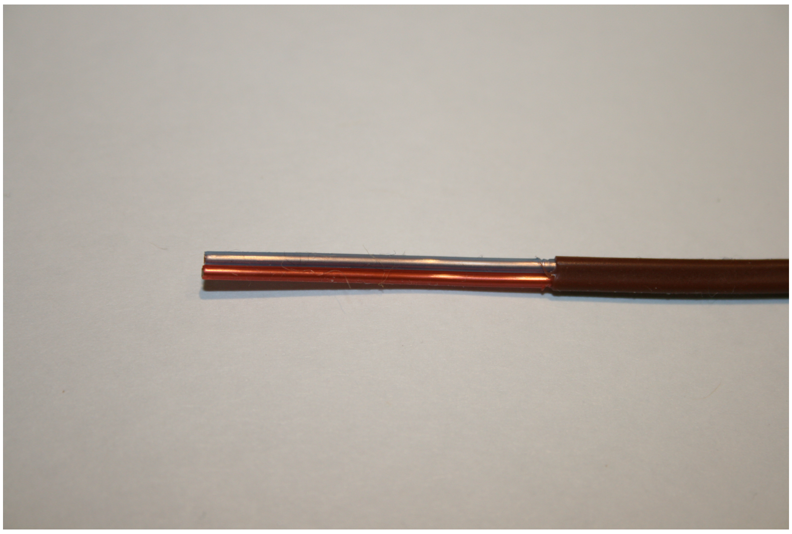


Figure 2.24: Thermocouple Manufacturing: Step 2. Thermocouple wire with the outer jacket stripped.

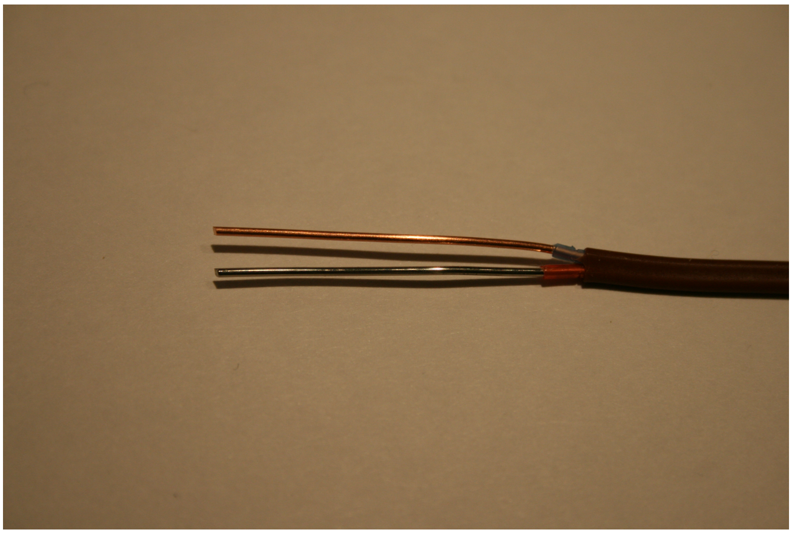


Figure 2.25: Thermocouple Manufacturing: Step 3. Thermocouple wire with the insulation stripped from the individual wires.

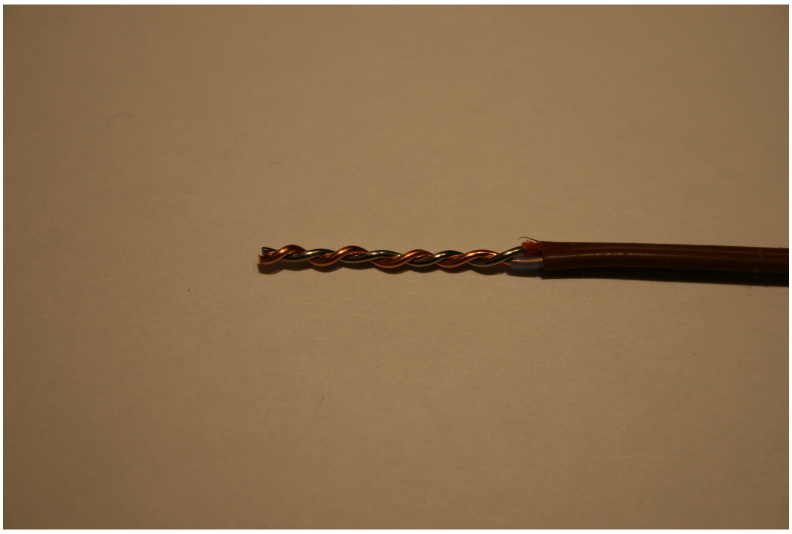


Figure 2.26: Thermocouple Manufacturing: Step 4. Thermocouple wire with the individual wires twisted together.

Figure 2.27: Thermocouple Manufacturing: Step 5. The finished thermocouple, after being dipped in liquid tape

on the initial conductivity test.

The boreholes were drilled using the drilling rig shown in Figures 2.28 and 2.29 with drill bits shown in Figure 2.30. The U-tubes were inserted in the casing for the drilling rig (Figure 2.31.) The boreholes were then grouted using a tremie pipe as the casing was removed. A U-tube after the vertical installation stages can be seen in Figure 2.32. At a later date, the three vertical U-tubes were connected and plumbed to the house with horizontal piping. The piping inside the house runs through the first floor mechanical room, up to the attic above the second floor where the heat pump and inline pump are installed (Figure 2.33.)

Of the three U-tubes installed for this system, only one was instrumented with thermocouples and a PEX pipe along its length. The thermocouples and PEX pipe were attached to the U-tube using duct tape every few feet (Figure 2.34.)

Figure 2.28: The Borehole Drilling Rig: View 1

Figure 2.29: The Borehole Drilling Rig: View 2

Figure 2.30: Drill Bits. These are two types of drill bits that screw onto the end of the drill casing driven by the drilling rig.

Figure 2.31: U-tube Insertion. The heavily monitored U-tube during installation, showing the U-tube, pex and TCs being inserted into the drill casing.

Figure 2.32: Vertical U-tube After Installation. This is the heavily monitored U-tube installed with a PEX pipe and thermocouples, before the horizontal pipes are connected. The U-tube is the two black pipes which are duct taped together and the PEX pipe is the smaller white pipe.

Figure 2.33: Heat Pump and Inline Pump. The heat pump and inline pump were installed in the attic above the second floor. The heat pump is the large, white device and the inline pump is the small, red device below the heat pump in the figure.

Figure 2.34: Bottom of a U-tube. A more detailed view of the bottom of a U-tube pipe with thermocouples duct taped in place. In reality, it looks more like a V than a U.

2.4.2 Thermosiphon System

The drilling contractor drilled an 80-foot well for the thermosiphon the same as if it were a U-tube. Once the well was drilled, the four 20-foot sections of galvanized pipe were connected piece by piece, with straight NPT couplings (Figure 2.35), and lowered into the drill rig casing. Once all of the pipe was lowered into the well, thermal grout was pumped into the well as the drill rig casing was pulled up. At a later date, a 1.5-inch to 1-inch adapter, 45 degree WYE elbow, and the heat exchanger assembly were screwed onto the previously installed thermosiphon pipe. PEX-pipe safe for propylene glycol mixtures and pac-joint fittings were used to plumb between the three-way valves and heat exchanger. The final heat exchanger and thermosiphon assembly was pressure tested with air to about 120 psi, for a period of a few days, to test for leaks. After the system passed pressure testing it was charged with R-134a refrigerant to approximately 40 psi.

Figure 2.35: Thermosiphon Coupling. One of the NPT couplings on the thermosiphon pipe during installation, shown with a PEX pipe and thermocouples.

2.5 Challenges

2.5.1 Field experiment vs. controlled lab environment

The amount of effort involved in setting up a field experiment versus an experiment in a controlled lab environment cannot be understated. Everything was more difficult: travel time to the site, set-up and tear-down time, weather, coordinating with contractors, damage to installed equipment by trucks and heavy machinery.

2.5.2 Human factors

The fact that this experiment was coordinated as part of a construction project and being built on an active construction site were enormous challenges. Coordinating with some of the trades was initially very hard for a number of reasons. They were upset because they were not made aware of our involvement when they accepted the job, and although coordinating with one more person does not sound like much, it only adds time and complication that was not factored into their original, fixed bid.

Being a student with classes, assignments and exams, not a full-time contractor, it was difficult to schedule work and coordinate installations with contractors. If they were working on something that I needed to be involved in, it did not matter what else was happening with school, I had to ignore all the other demands on my time and be working at the site. Unlike normal graduate projects where code, or lab experimental set-ups that are just the same as when you left them before you got pulled away for a few days, things on the construction site were rarely the same as when you left them.

Being a young, inexperienced engineer was another challenge in and of itself. Having little applied experience with many of the involved trades (plumbing, electrical, drilling) my initial plan often had fatal flaws which were glaringly obvious to veterans in the trades. With that said, I gained an enormous amount of practical knowledge from the tradesmen. The entire design and construction phase was a crash course in plumbing, electrical, drilling, excavation and HVAC.

There were approximately 50 thermocouples in the field. Many of these needed to be extended or shortened which resulted in renumbering the wires more than one time. Although renumbering was done with the utmost care, checking and often double checking the numbers, it is possible that errors could have been introduced during this procedure.

2.5.3 Weather

Starting installation of a field experiment above an elevation of 6,000 feet in Utah during the fall caused a lot of major delays. Drilling was sometimes on hold until the ground thawed in the morning. Cold weather slowed the entire pace of the project. Once it got late enough in the year, snow accumulation halted work on the GSHP system (Figure 2.36.)

The adhesive in duct tape loses its stickiness around freezing temperatures, which at times made it very difficult to attach thermocouples to the plastic pipe used for the GSHP. In this case, the back up solution was quick (zip) ties, but these were brittle and sometime broke at the cold temperatures.

Figure 2.36: Snow During Construction. Weather drastically slowed the pace of construction.

2.5.4 Inexperience

Choosing the right materials would have saved a lot of time and effort, but these decisions were hard to make with little to no experience performing many of these tasks. The thermocouples running from the U-tubes and thermosiphon back to the house were run through PVC to weatherize and protect the wires. The problem was that the PVC which was chosen was irrigation PVC, the white kind, versus electrical PVC, the gray kind. This made pulling bundles of thermocouple wire through T or elbow fittings much more difficult because this was not the intended purpose of these materials.

Using stranded as opposed to solid core thermocouple wire would have made installation easier. Stranded wire would have been better than solid core wire because its superior pliability would have been substantially easier to pull through the conduit.

Choosing the pex pipe and associated NPT adapters connecting the thermosiphon heat exchanger to the three-way valves ended up being a process that required multiple revisions. Due to lack of experience, plain PEX and Jones fittings were installed. After consulting with the on-site plumber, oxygen-barrier PEX and pac-joint fittings were used to replace the original materials. The PEX pipe was changed because standard PEX is not compatible with glycol mixtures. The Jones fittings were replaced with pac-joint fittings because the Jones fittings are leak-prone and the pac style fittings are very dependable. These changes helped ensure that this unconventional, unrated implementation of these materials yielded the most reliable system possible in order to protect the ground water purity.

CHAPTER 3

U-TUBE HEAT TRANSFER

3.1 Short Term Analysis

3.1.1 U-tube Inlet and Outlet Temperatures

The three highest temperatures during the majority of the test shown in Figure 3.1 are the outlet temperatures for each borehole and the three lowest are the inlet temperatures.

Overall the three inlet temperatures are well grouped together and the three outlet temperatures are well grouped together. This is as predicted because the three boreholes are connected in parallel.

The temperature differences among the inlets is more pronounced than that for the outlets. It is assumed that this greater difference in the inlets is caused by variations in the horizontal tubing along the fluid path. This includes variations in the length of the horizontal run and the variations in geology and ground temperatures in the different horizontal runs.

3.1.2 U-tube Instrumentation

Geothermal contractors and installers do not differentiate between an inlet or outlet during installation because it makes no difference in terms of system performance. The thermocouples on the U-tubes were installed ‘blind,’ without specifying the inlet or outlet side of the U-tube. The BH1 25ft, BH1 50ft - 1, BH1 50ft - 2, BH1 75ft and BH1 Bottom thermocouples were all installed on the heavily monitored U-tube during installation of the vertical borehole. The borehole inlet and outlet thermocouples were all installed during the horizontal phase.

The identification of inlet versus outlet thermocouples was based on observing the temperatures during heat pump operation; the inlet temperature is always

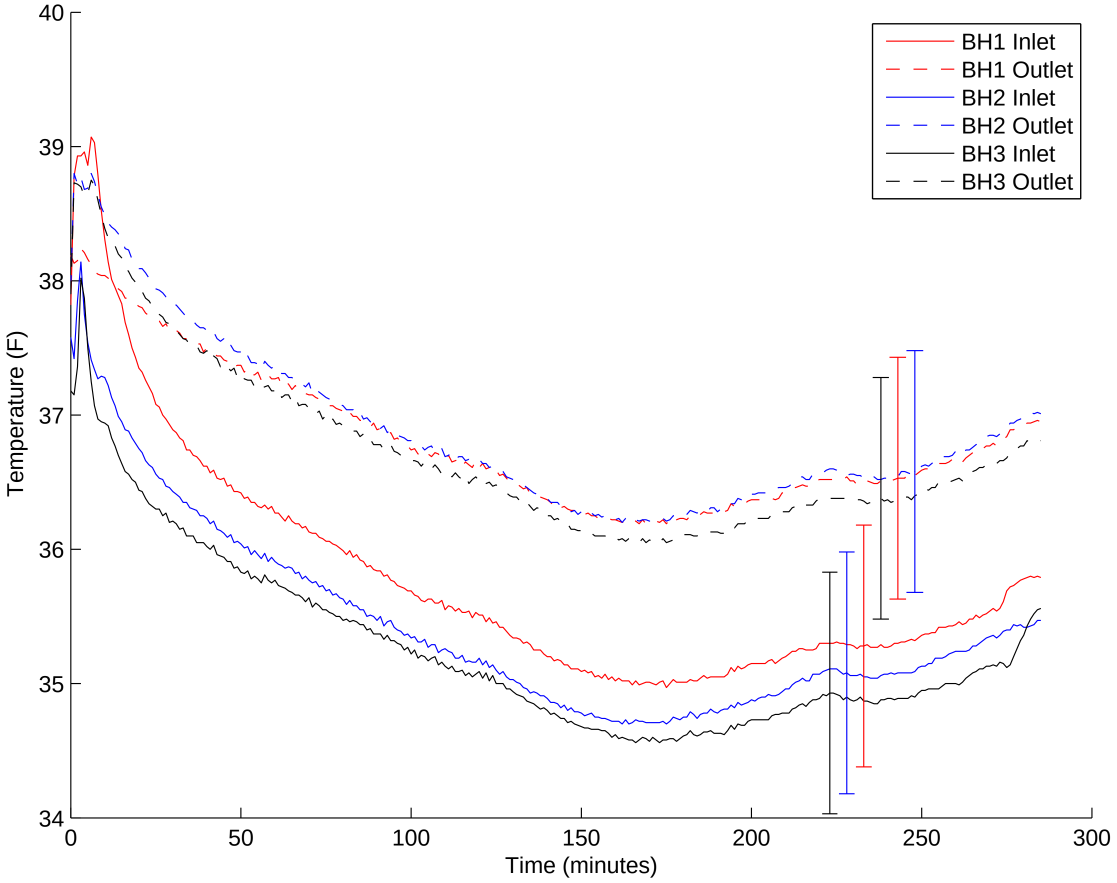


Figure 3.1: U-tube Inlet and Outlet Temperatures. The solid lines indicate the U-tube borehole inlet temperatures and the dashed lines indicate the U-tube borehole outlet temperatures.

significantly lower than the outlet temperature (Figure 3.1.)

Identifiying the orientation of the heavily monitored U-tube was based on the thermocouple groupings and the temperature decay rate of one thermocouple with respect to another. The potential orientations for the heavily monitored U-tube can be seen in Figure 3.2. It was deduced that the orientation of Borehole 1 is scenario two.

3.1.3 Temperature vs. Time for the Heavily Monitored U-tube

Data from typical cycling of the GSHP system did not give temperatures that well represented the fluid temperature at the corresponding locations in the borehole field. During system cycling, for shorter time periods, 15 to 30 minutes, while the thermostat was trying to maintain a constant set point, it was difficult to derive any meaning from the temperatures along the length of the loop because they are so erratic. This is most likely due to the initial heat transfer rates being particularly sensitive to varying hydrological and geological conditions.

The multihour endurance test results can be seen in Figure 3.3. Although the temperatures along the length of the U-tube are not as representative as expected, the inlet temperature is cooler than all of the other thermocouples on that specific U-tube. Another important conclusion is that the outlet is warmer than the inlet for almost the entire test, representing a positive heat flux. In spite of the uncertainties related to location of the thermocouple on the U-tube, all of the temperatures except for one of the 50 foot measurements are above the temperature of the outlet, indicating that the GSHP fluid cools on its path back up the U-tube.

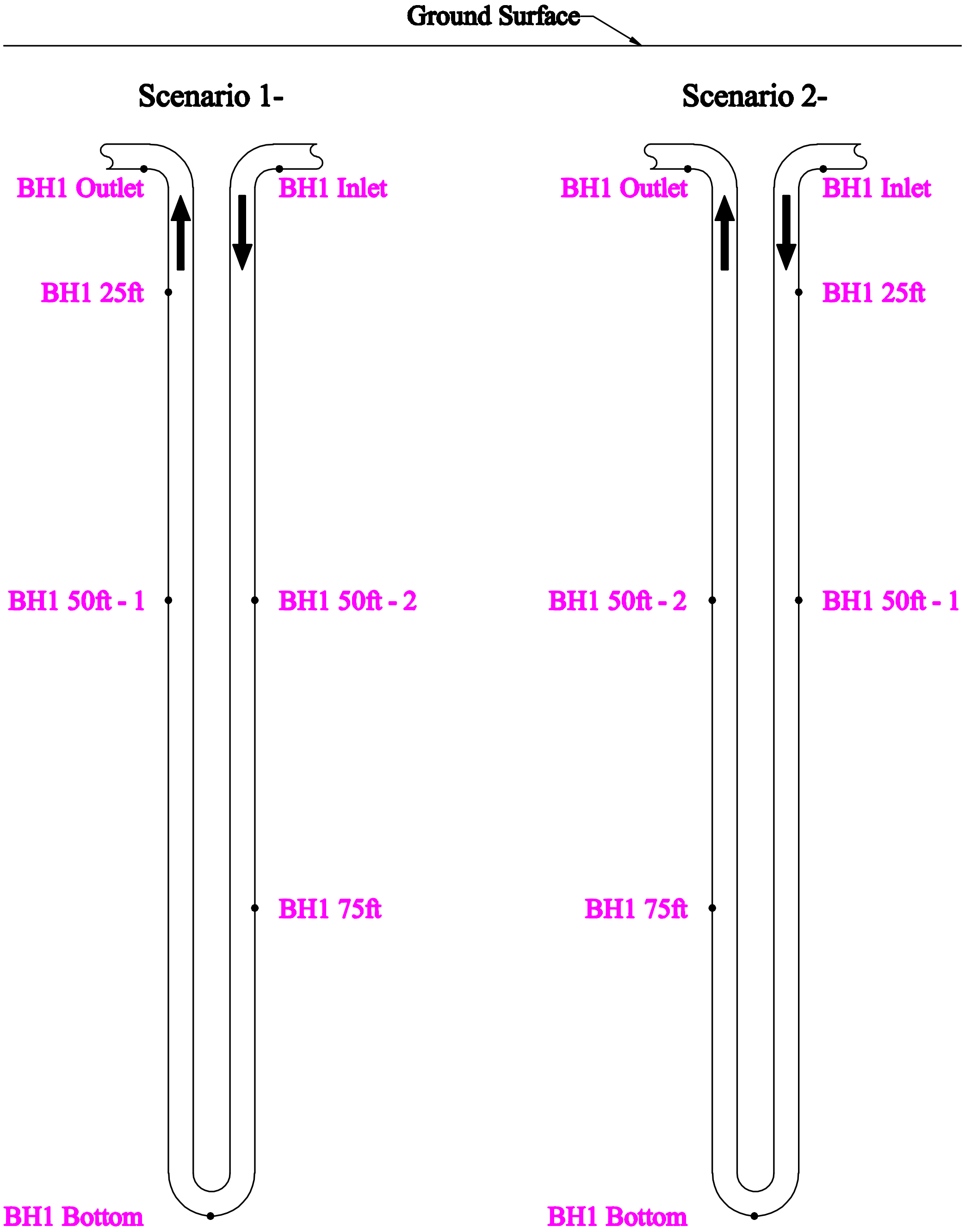


Figure 3.2: U-tube Borehole 1 Vertical Section View. The U-tubes were installed ‘blind,’ meaning that one side was not specified as an inlet and the other as an outlet because this does not affect the functioning of the system. At the time of installation, it was not known by the author that the U-tubes were installed ‘blind’ and there is some ambiguity as to which scenario the thermocouples are oriented in.

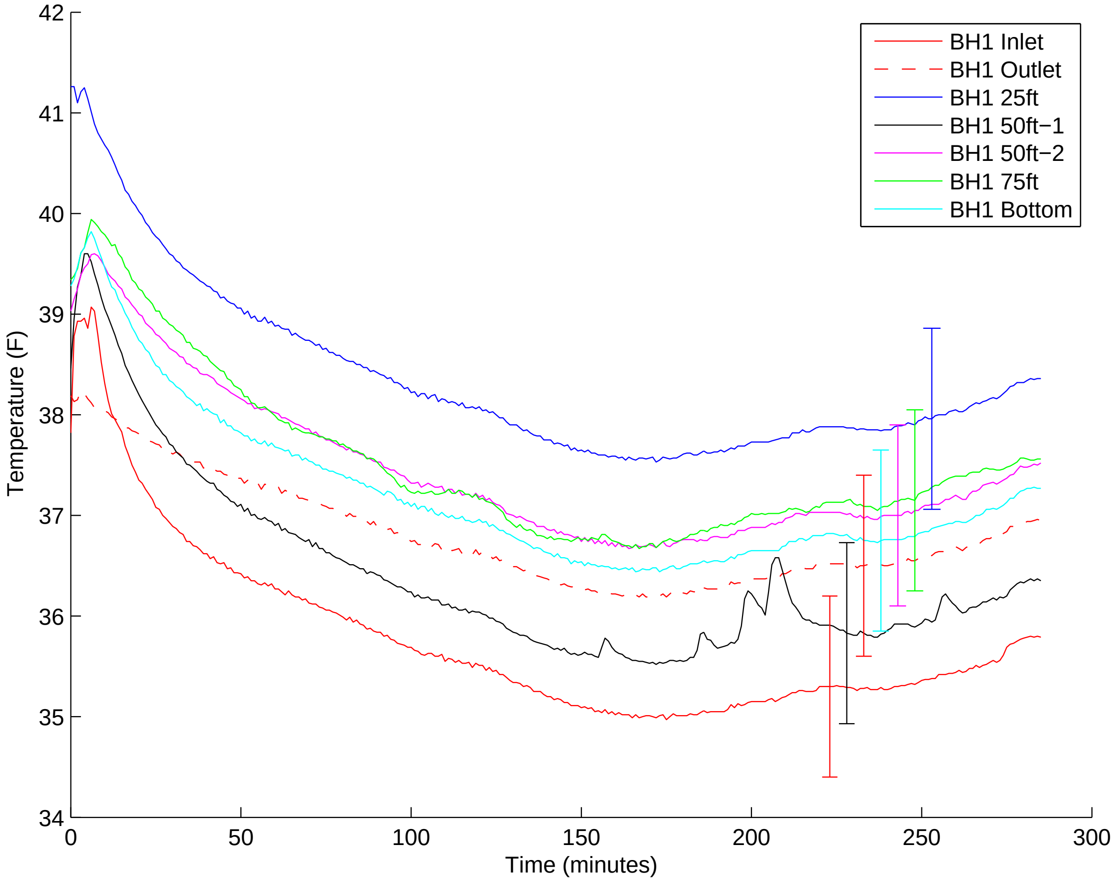


Figure 3.3: U-tube Temperatures vs. Time. The temperatures along the length of the U-tube borehole decay over time, as heat is removed from the near-field region. For the majority of the time, the outlet temperature is above the inlet which confirms that heat is being extracted from the ground. The outlet temperature also indicates that the fluid is cooled as it returns on the outlet side of the U-tube because for the most part, it is the third coldest temperature along the length of the U-tube.

3.1.4 Immersed compared to surface mounted thermocouple temperatures

There was an additional set of thermocouples measuring the inlet and outlet temperatures to the heat pump. In Figure 3.4, it can be seen that the surface mounted thermocouples were about 5° F warmer and have a greater temperature difference between inlet and outlet than the immersed thermocouples. This discrepancy between the immersed and surface thermocouples can be attributed to warming of the fluid once it enters the house. After the fluid penetrates the floor in the first floor mechanical room, it travels in uninsulated piping to the heat pump for the GSHP system, located in the attic above the second floor in the house. The immersed temperatures are measured just above the floor in the first floor mechanical room, but the surface temperatures are measured just before the heat pump in the attic. Heat transfer between the fluid in the uninsulated and the house create this temperature difference. The immersed thermocouples represent the true performance of the geothermal system because when looking at the building from a control volume standpoint, they are the fluid temperatures at the boundary of the control volume.

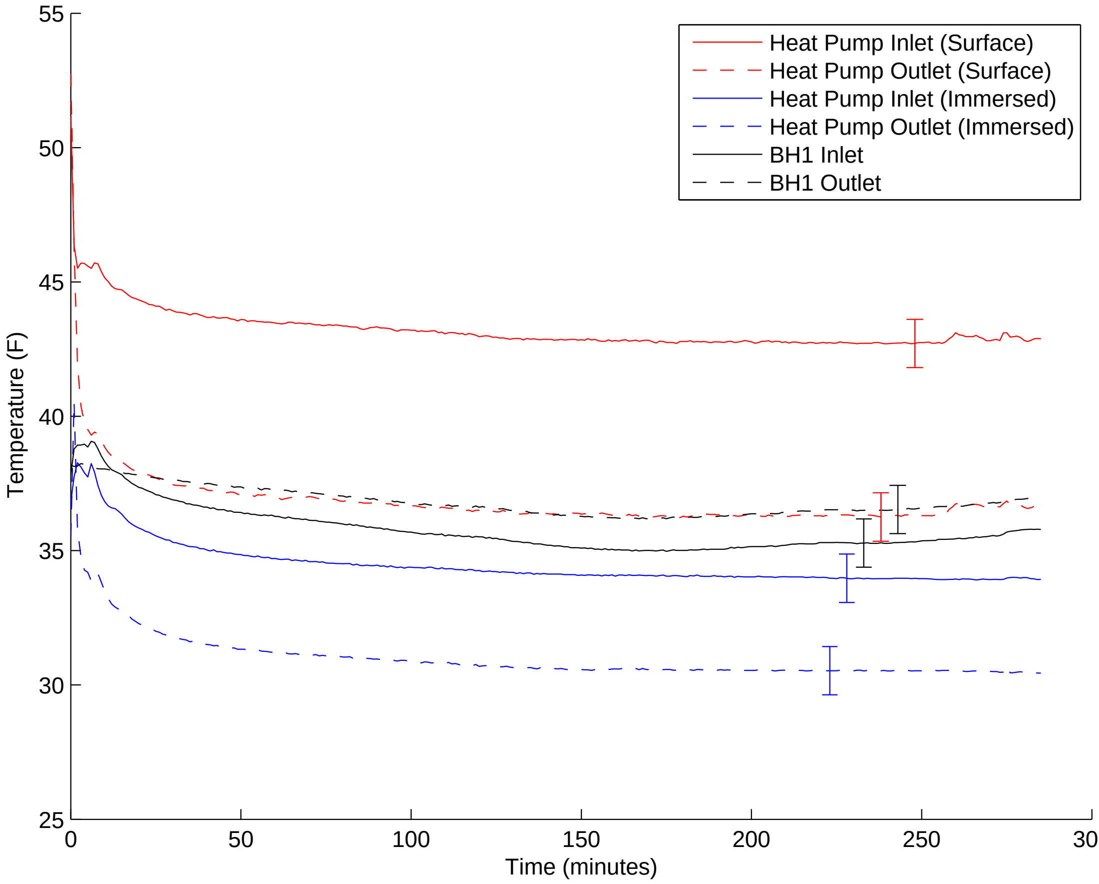


Figure 3.4: Immersed vs. Surface Temperatures for the U-tube System. The discrepancy between the immersed and surface mounted thermocouple temperatures is due to their different physical locations inside the building. Heat transfer between the pipes and the indoor environment occurs because the pipes are uninsulated on inside the house.

CHAPTER 4

THERMOSIPHON HEAT TRANSFER

4.1 Short Term Analysis

4.1.1 Temperature vs. time at multiple locations

Temperature histories at various depths on the outside wall of the TS pipe and the inlets and outlets of the heat exchanger are shown in Figure 4.1. The R134a temperatures at the inlet and outlet of the heat exchanger are almost identical during the period shown. This indicates that the heat transfer is occurring due to condensation. The glycol temperatures between the inlet and outlet represent a relatively constant temperature difference meaning that the thermosiphon is extracting heat from the ground at a constant heat flux.

The 'shoulders,' or rapid temperature drops in the TS 50 and 75 foot thermocouples are caused by a delay in refrigerant reaching those locations on the thermosiphons. Starting from inactivity, once the heat exchanger has 'cold' glycol fluid circulating through the tube side, refrigerant starts condensing on the shell side of the heat exchanger. As this condensation occurs, the liquid refrigerant is returned to the thermosiphon due to gravity. As it travels down the walls of the thermosiphon, it saturates the mesh material, hardware cloth, as the liquid front moves down the pipe. The 'shoulders' occur in the temperature profile as the liquid refrigerant front reaches the location of a thermocouple because once the refrigerant saturates the mesh at the inside wall of the pipe, refrigerant vaporization occurs. Once refrigerant has reached the entire interior area of the pipe, the temperatures at TS 25, 50 and 75 stabilize at the same temperature, around 41° F .

Unlike the TS 50 and 75 profiles, there is no 'shoulder' in the TS 25 temperature profile. The thermocouple at the TS 25 location is only 5 feet from the top of the thermosiphon pipe. Therefore the response time is very short for the liquid refrigerant to reach that location once condensation starts at the heat exchanger.

The immediate drop in the temperature of TS 100 at the bottom of the thermosiphon pipe is also observed and thus the liquid in the bottom began vaporizing as soon as the cooling of the condenser dropped the thermosiphon pipe pressure. The TS 100 thermocouple temperature stabilizes at a higher temperature than the other TS temperatures because it is located at the bottom of the thermosiphon where there is a column of liquid refrigerant in bottom of the pipe. This column creates a higher pressure at the bottom of the thermosiphon which increases the boiling temperature of the refrigerant above that at the top surface of the liquid column.

4.1.2 Immersed compared to surface mounted thermocouple temperatures

The immersed versus the surface mounted thermocouple measurements in the thermosiphon test (Figure 4.2) are different for the same reason that they were different in the U-tube test, heat transfer to uninsulated pipes inside the building.

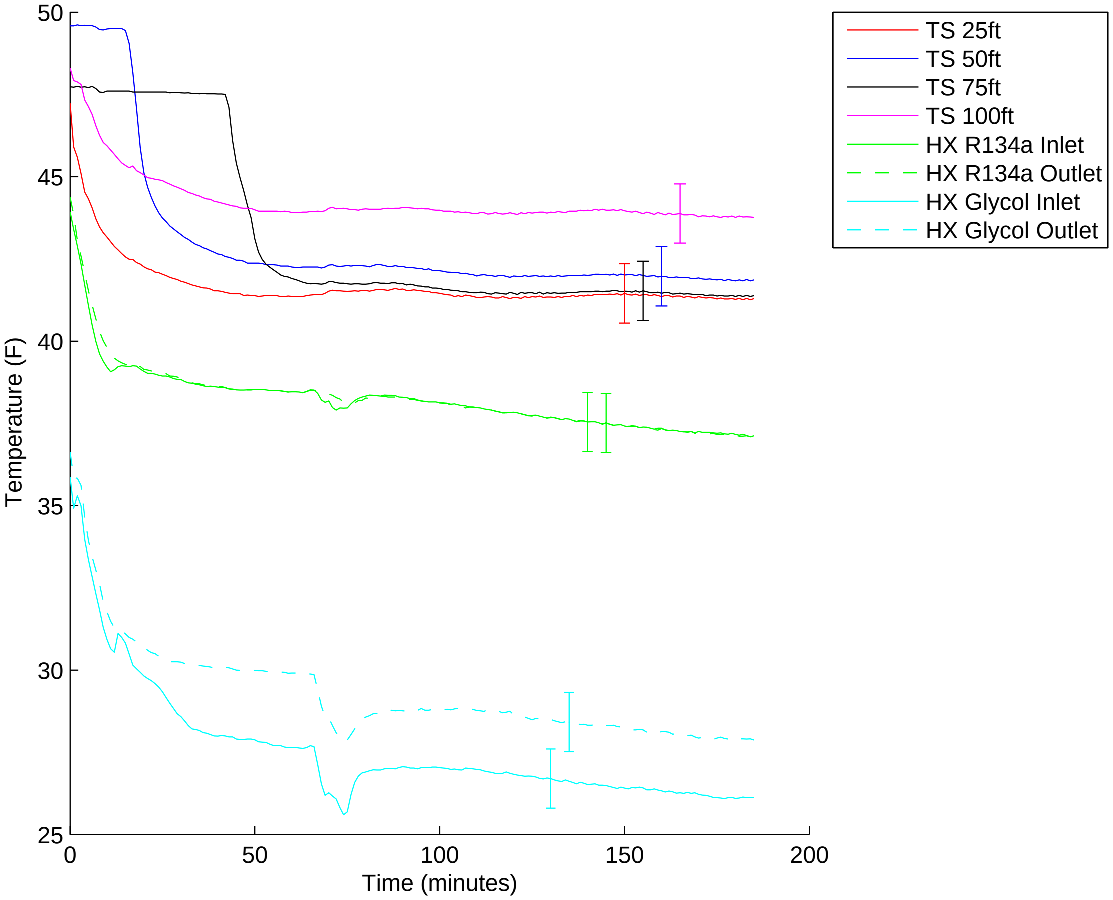


Figure 4.1: Thermosiphon Temperatures vs. Time. This figure shows the thermosiphon outside wall and heat exchanger temperatures as a function of time. The tight grouping of the HX R134a Inlet and Outlet temperatures indicates that the thermosiphon is operating as a phase change device. The temperature difference between the HX Glycol Inlet and Outlet is relatively constant throughout the test indicating a constant heat flux into the thermosiphon. The step shaped decay of the TS 50ft and TS 75ft is caused by the delay in refrigerant saturating the mesh and inside wall of the thermosiphon pipe at those locations because a refrigerant must be at those locations for an significant temperature response due to vaporization.

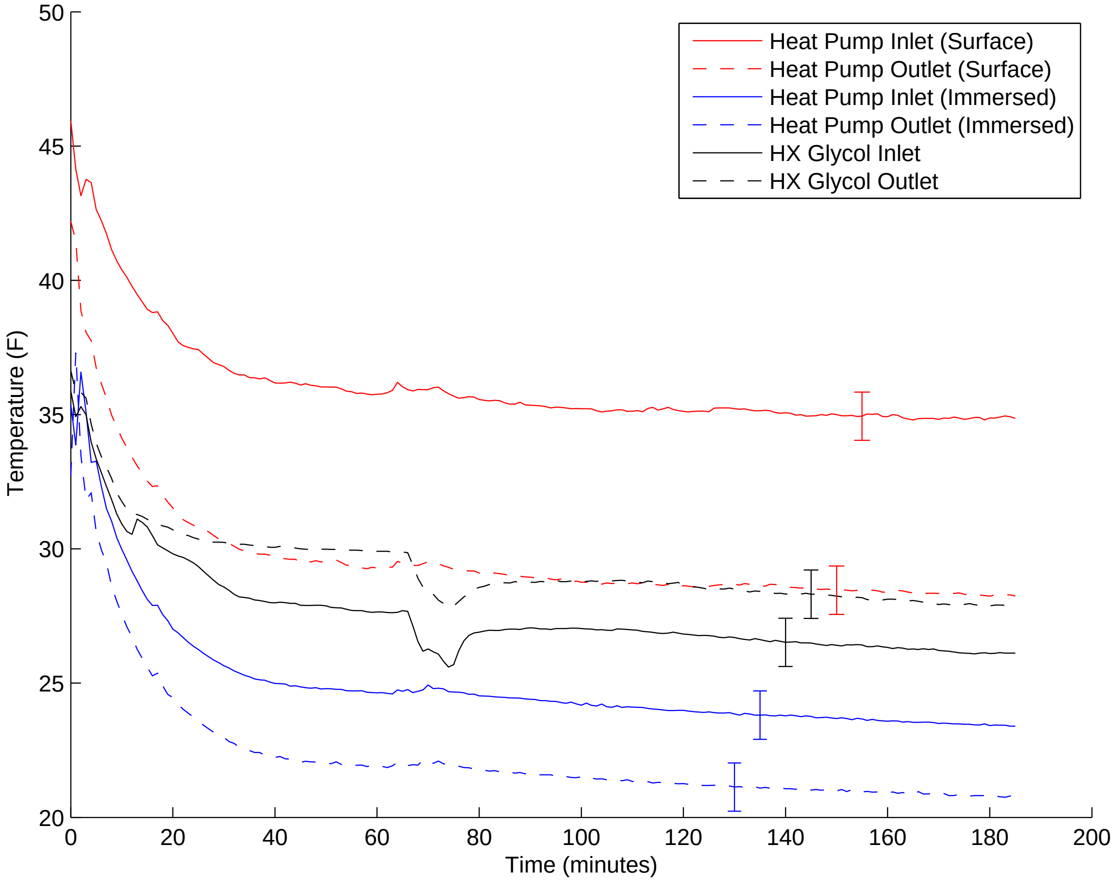


Figure 4.2: Immersed vs. Surface Temperatures for the Thermosiphon System

CHAPTER 5

THERMAL EXTRACTION AND HEAT PUMP ANALYSIS

5.1 Heat absorbed by the heat pump

For the control volume of interest:

$$\dot{Q}_L = \dot{m} \cdot c_p \cdot \Delta T \tag{5.1}$$

$$\dot{Q}_L = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \tag{5.2}$$

5.2 Heat absorbed by the heat pump per unit length of borehole

Figure 5.1 shows that the $\dot{Q}_{L,normalized}$ for the feet of borehole for the thermosiphon is substantially higher than that for the U-tube borehole. Based on the results from this test the thermosiphon has approximately two times the heat transfer capability per foot of borehole. The thermosiphon performs so much better because it does not have have the performance robbing cancellation that U-tubes suffer from and the latent heat of vaporization yields a very low thermal resistance.

This result has a significant impact on the initial capital cost of installing either a U-tube or a thermosiphon system. Borehole drilling costs are typically the most significant capital expense for a small scale geothermal system such as ground source heat pumps. For heating applications, this means that drilling costs could be cut in half through the use of thermosiphons instead of U-tube, drastically reducing first cost of the system.

One factor that could not be accounted for in the comparison is that the U-tube had already operated for a portion of the heating season on the day that the comparison testing was performed, while the thermosiphon had not been operated prior to that day. This means that ground temperatures were already slightly suppressed around the U-tubes because heat had been extracted from the local soils.

$$\dot{Q}_{L,normalized} = \frac{\dot{Q}_L}{Total\ Borehole\ Length} \tag{5.3}$$

5.3 COP

5.3.1 Comparison of U-tube to Thermosiphon COP

The COP of the U-tube and thermosiphon systems during the short term tests was calculated using the following equation for COP.

$$COP_{HP} = \frac{Q_H}{W_{net}} \tag{5.4}$$

$$= \frac{W_{net} + Q_L}{W_{net}} \tag{5.5}$$

$$COP_{HP} = \frac{\dot{W}_{net} + \dot{Q}_L}{\dot{W}_{net}} \tag{5.6}$$

The COP of the heat pump for the U-tube borehole system is slightly better than the COP for the thermosiphon system (Figure 5.2). This calculation is in no way normalized for the different length of boreholes between the two systems. Therefore the U-tube system has a higher COP only due to the fact that it has three times the length of borehole.

5.3.2 Seasonal U-tube COP

The daily average COP of the U-tube system was calculated in order to see if there is a decline in efficiency throughout the heating season as heat is extracted from the ground. The daily average was calculated by averaging the COP on a daily basis only for times that the system is running. A least squares fit was applied to the daily averages in order to determine the COP trend for the heating season. The results of this study can be seen in Figure 5.3.

As predicted, the daily average COP of the U-tube system declines throughout the heating season as indicated by the negative slope of the least squares fit line

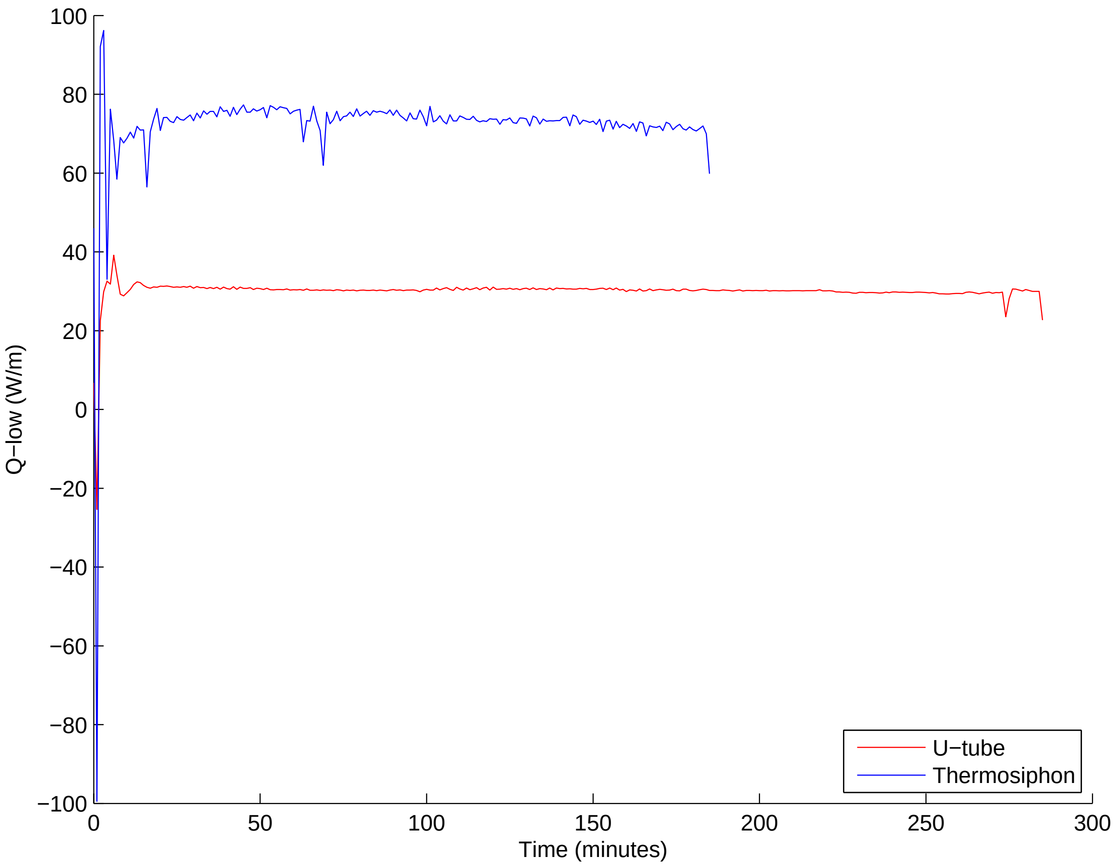


Figure 5.1: Q-low per Foot of Borehole Comparison. The thermosiphon extracts approximately twice the heat from the ground per foot of borehole than the U-tube. The phase change nature of the thermosiphon is not susceptible to the thermal interference that afflicts the U-tube design. The heat transfer per foot of borehole is important because borehole drilling is one of the most significant, if not the most significant, capital cost in a small scale geothermal system. The calculated error in this figure is on the order of 1e-11.

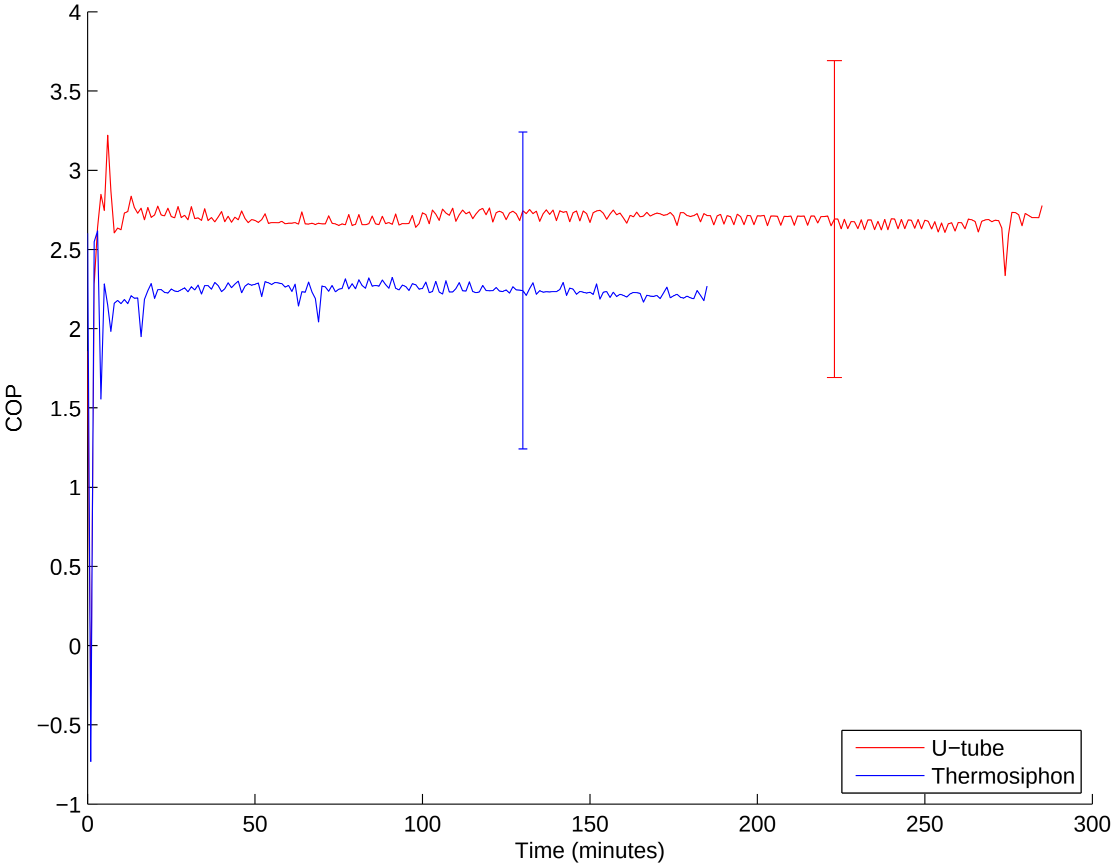


Figure 5.2: COP Comparison. The COP of the U-tube is slightly higher than the COP of the thermosiphon over the majority of the test. These data are not normalized for the length of borehole. Therefore the U-tube has a higher efficiency. The U-tube performs better only because it has three times the length of borehole.

in Figure 5.3. This occurs because as heat is extracted from the ground local soil temperatures around the U-tube are depressed. The depressed soil temperatures lead to a lower ΔT in Q_L, and therefore a lower COP, or system heating efficiency.

Another important finding is that the daily average COP is below 3 during the monitoring period. Ground source heat pump literature typically estimate system COPs to be between 4 and 5. A COP of 3 is particularly important because 3 represents the efficiency at which the operating (fuel) costs and carbon footprint are roughly equivalent to a high-efficiency natural gas furnace. Electricity is roughly 3 times more expensive than natural gas, which means that comparing a ground source heat pump to a high-efficiency furnace, with a thermal efficiency of almost 100%, the heat pump system must use less than one third the electrical energy (a COP greater than 3) in order to have a lower operating cost. A GSHP system COP of less than 3 also means that the GSHP system will likely have an infinite payback period because on average GSHP systems are more expensive than an equivalent capacity gas powered furnace. At less than 3, the carbon footprint is also greater assuming that the electricity is generated from a natural gas fired power plant because the efficiency of the overall electricity, including generation and transmission, once it reaches the consumer is roughly 33%.

5.4 Comparison of ground source to an air source heat pump

When considering the application of a ground source heat pump system, it is important to compare the seasonal ground temperatures to the seasonal air temperatures during the intended period of use, in this case the heating season. This comparison is important because the initial cost of a ground source heat pump system is much higher than a comparably sized air source heat pump system. A prospective GSHP system should have a more favorable source temperature than an air source system in the same location, therefore providing improved efficiency to compensates for the higher initial cost. In Figure 5.4, the heat pump inlet temperature is higher than the ambient air temperature during the majority of the analysis period. This means that the ground as a heat source is thermodynamically favorable to the air as a heat source for the heat pump system.

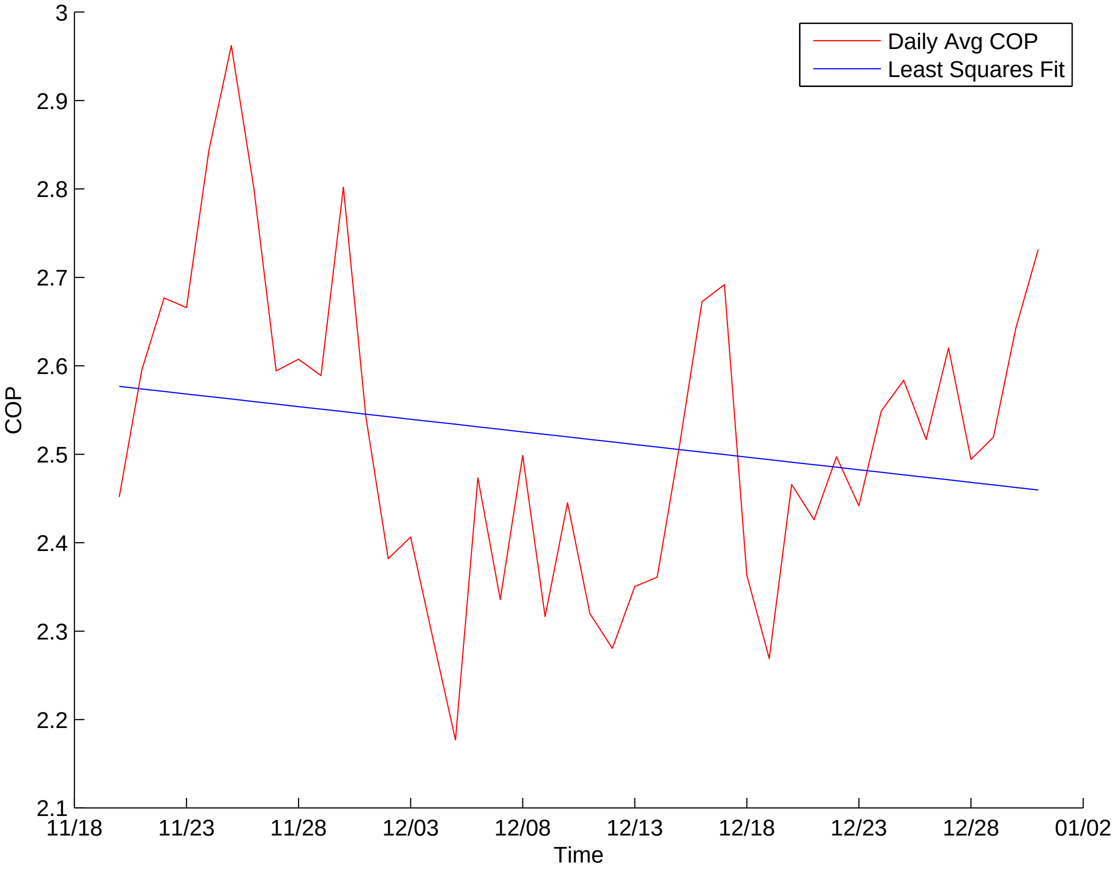


Figure 5.3: Average Daily COP. The average daily COP, calculated only for time when the system was actually running, was less than 3 for the entire duration of the test. The COP declines during the heating season, as shown by the negative slope of the least squares fit line. The COP had a decline of .0029 per day or roughly .086 per month.

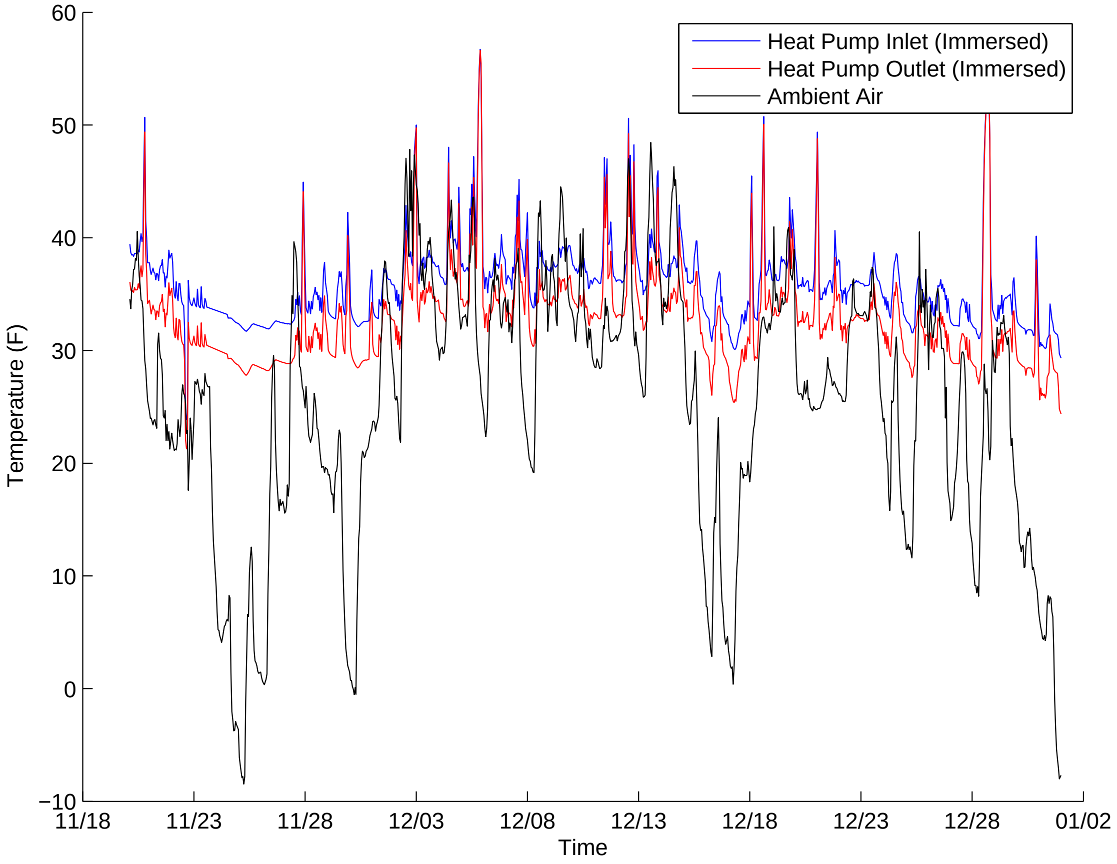


Figure 5.4: Comparison of U-tube System Temperatures to Ambient Air Temperatures. This comparison verifies that the ground is a better heat source for the heat pump than the ambient air. For 86% of the period analyzed, the heat pump inlet temperatures are above the ambient air temperatures, which makes the ground a more favorable heat source.

CHAPTER 6

CONCLUSIONS

6.1 Findings

The data indicate that the thermosiphon has roughly two times the heat extraction rate compared to the U-tube per foot of borehole. U-tube performance was shown to decline through the heating season.

GSHP *COP* calculated to be less than 3, which is much lower than typically estimated values of 4 to 5. When looking at the potential of GSHP as an energy and cost saving technology, one must consider that although there is a high level of confidence in the results, that this is one GSHP installation, designed by one engineer and installed in one location with its own unique geology and hydrology.

6.2 Challenges

Given the fact that this experiment was carried out on a working construction site, with deadlines and standard installation procedures, it was extremely challenging to foresee all of the potential obstacles and install experiment exactly as planned.

The weather slowed the planned schedule and caused major road blocks in the installation of the experiment. It is very difficult to create a realistic schedule when it comes to planning around weather during winter at high elevation.

6.3 Recommendations

It would be valuable to duplicate the U-tube monitoring on another GSHP system. Comparing U-tube installations with and without spacer to separate the two pipes would be a valuable side-by-side comparison.

The most important recommendations generated from this experiment are probably with respect to choice of materials. If allowable, thermistors would be a better choice of sensor for temperature measurement than thermocouples given their superior accuracy. No matter what type of sensor used, it is advisable to use stranded wire instead of solid core wire because the greater flexibility of stranded wire will ease installation. Using electrical PVC pipe as conduit instead of standard irrigation PVC pipe will also ease the installation of wires.

Due to the nonsymmetrical heat transfer in the two sides of a U-tube and the lack of contractor designation between inlet and outlet, it would be best to instrument both sides equally. Insulating around the outer diameter of the U-tube pipe where a temperature sensor is located would aid in the measurement of fluid temperatures instead of a combination of fluid and ground temperatures that is measured in this experiment.

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