UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

STUDYING A MORE EFFICIENT AND COST-EFFECTIVE GEOTHERMAL SYSTEM: ENHANCING HORIZONTAL GEOTHERMAL SYSTEM WITH WATER FLUX PROVIDED BY SEPTIC WASTEWATER

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

JASON D. BEATY

Norman, Oklahoma

2025

STUDYING A MORE EFFICIENT AND COST-EFFECTIVE GEOTHERMAL SYSTEM: ENHANCING HORIZONTAL GEOTHERMAL SYSTEM WITH WATER FLUX PROVIDED BY SEPTIC WASTEWATER

A THESIS APPROVED FOR THE
SCHOOL OF AEROSPACE AND MECHANICAL ENGINEERING

BY THE COMMITTEE CONSISTING OF

Dr. Li Song, Chair

Dr. Feng C. Lai

Dr. Dong Zhang

Acknowledgements

First, I want to thank my beautiful wife, Deana, for supporting me in my endeavor to go back to school and earn my master's degree.

Secondly, I want to thank my advisor, Dr. Li Song, for giving me an opportunity to work on her Shawnee, OK project and pushing me to pursue my master's by developing a thesis. I want to thank her for the support and teaching on researching and writing my thesis, writing a paper for ASHRAE, that's been excepted for presentation. Also, I would like to thank the research team from the Shawnee, OK project. Dr. Xingru Wu, for his work on soil thermal conductivity and providing his knowledge to me. Rodney Hurt, for helping build my modeling program. Andrew Ejenakevwe, for helping me de-bug my simulation. And Nurayn Tiamiyu, for helping me start my simulation model.

Thirdly, I would like to thank my family and friends for supporting me and giving me words of encouragement to keep pushing for my goal of completing my degree.

Last, I would like to thank the United States Airforce for giving me this opportunity to pursue and earn my master's degree.

Table of Contents

List of Tables

List of Figures

Abstract

It is well documented and understood that consumption of energy is always increasing worldwide as the population grows. According to the U.S. Energy Information Administration [EIA] in 2023 the electricity sales to the four end user sectors, transportation / industrial / residential / commercial, residential consumed 38% of it. Residential also consumed 23% of natural gas, 3% of petroleum, and 15% of renewable energy of the four end user sectors. In 2020 US homes consumption of energy, on average, 52% was used for space heating and air conditioning (HVAC).

Since most of the residential energy is consumed for HVAC, it has the potential to produce the largest energy savings by using a more efficient system. A heat pump (HP) is more efficient at conditioning a space than the more commonly used types, direct expansion, electric resistant, and natural gas. Unfortunately for heat pumps, they lose their efficiency advantage when operated outside of their ideal temperatures, between 40º F and below 80º F. That's why geothermal water source heat pump systems are more efficient, their typical operation is around 67º F.

The problem with geothermal systems compared to traditional units is the greater increase in installation costs. Of the two most common systems, vertical ground and horizontal ground, vertical is the most efficient but has the highest installation cost and takes the most specialized equipment to install. So, the dilemma is, how can we make the horizontal ground geothermal system more efficient and affordable at the same time. By solving this problem, we can give more opportunities to save on the consumption of energy and cost of better technologies.

A proposed solution is to combine horizontal geothermal and septic systems together. The footprint of the geothermal field would be installed under the septic lateral field in a layered configuration. This way the geothermal will benefit from the wastewater of the septic in increasing thermal conductivity, heat flux of the soil, making the geothermal more efficient. Also, the construction cost for the combined systems will be lower than if they were built separately.

The paper includes a study of the proof of concept using modeling software Dymola and known soil characteristics of Shawnee, OK showing the increase of soil thermal conductivity, heat flux of the system. The difference of normal soil conditions vs saturated soil conditions will be researched for this paper. Efficiency, cost comparisons, and life cycle analysis will be shown against several commonly used systems. The common systems are air source HP, horizontal geothermal HP, and vertical geothermal HP. Through our study, we have found the coefficient of performance (COP) of each system to be different. The improved COP of the horizontal geothermal HP system resulted in higher energy savings. The life cycle cost analysis shows that it takes 4 - 9 years for return on investment. Final remarks and future research for this combined system will also be discussed.

Chapter 1: Introduction

1.1 Conditioning of Space

Humans have always been trying to condition the space they dwell in. Using fires for heating, being one of the oldest ways of space conditioning, they also had to ensure the smoke had a path out of their dwelling. Ancient societies like the Romans designed their buildings to increase natural airflow throughout the structure, and they even pumped water through the walls for a cooling effect [Ellen Hunter, 2023]. Over time the process of conditioning spaces became better and more controlled. With the development of modern heat, ventilation, and air conditioning (HVAC) systems, the focus is on achieving the same space conditioning requirements with lowered energy consumption.

1.1.1 Heat Pumps

Heat pumps (HP) transfer heat from one zone to another through the refrigeration cycle process. They are typically more efficient than common systems like direct expansion (DX), which share a similar heat transfer mechanism, combined with electric-resistive heating and gas furnaces. In most circumstances, air source heat pump (ASHP) systems outperform these combined DX and heating systems, especially in heating cycles. ASHP generally achieve a higher coefficient of performance (COP), the ratio of heat output to energy input, typically ranging from 3 to 4, compared to the combined systems heating, which average around 1. Heat pumps are also rated by their SEER, seasonal energy efficiency ratio, cooling output to energy input. Similar COP but only looks at the cooling cycle and is used mostly for residential units. Figure 1.1 below is a simple diagram of how heat pumps work, more specifically, an ASHP. The cycle can be reversed depending on heating or cooling of the space. Whatever the medium the heat pump exchanges energy with, it can heat or cool the space it is affecting.

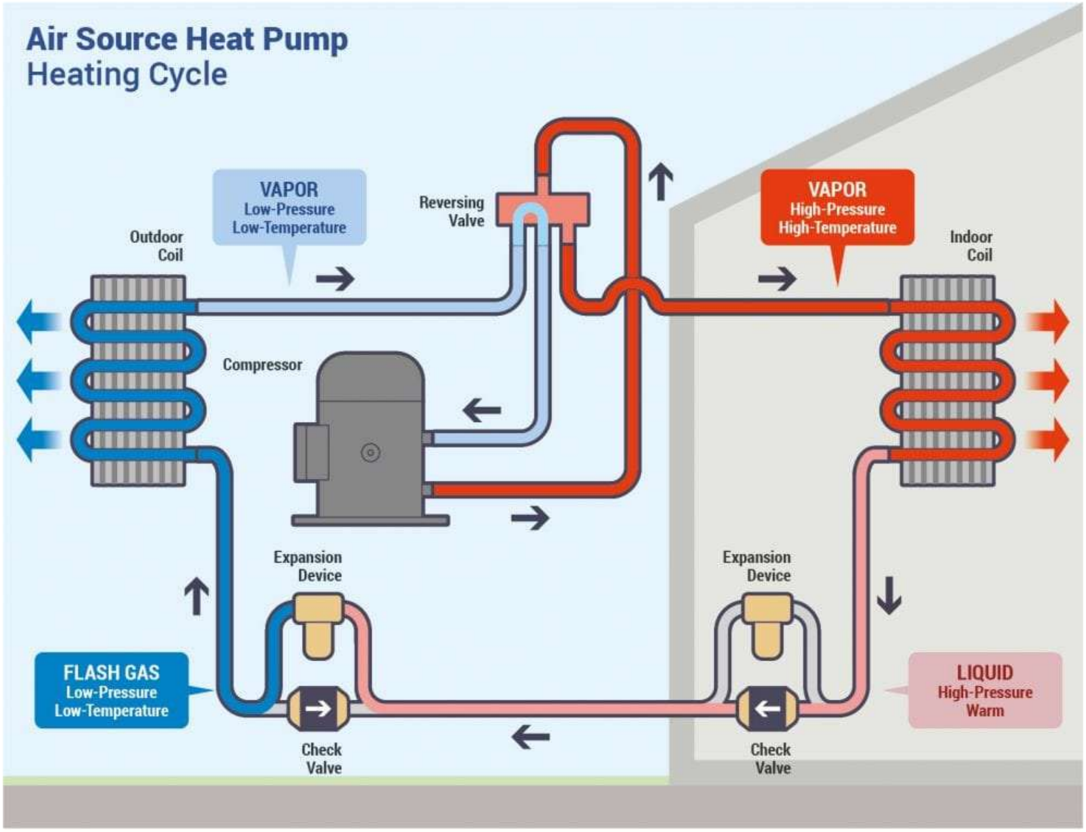


Fig. 1.1 ASHP Heating Cycle (HVAC School)

However, in extreme high or low temperatures, ASHP lose their efficiency advantage compared to common heating and cooling systems. To address this, combined systems such as ASHP paired with gas furnaces can mitigate efficiency issues in colder climates. Alternatively, water-source HPs maintain higher efficiency due to their operation within a narrower temperature range, staying closer to optimal conditions. Water-source systems can be open-loop, utilizing water from lakes or rivers, or closed-loop, circulating water through pipes connected to cooling towers, bodies of water, or geothermal with the pipes buried underground.

Beyond efficiency, HPs help reduce or even eliminate the use of fossil fuels at the point of conditioned spaces. This transition alleviates environmental impacts and health concerns associated with fossil fuel use.

1.1.2 Geothermal

Geothermal, ground-source for HVAC systems, is where the loop for exchanging energy is buried underground. This allows the system to use the earth's more constant temperature to provide a stable source of energy, or battery one could say. During the cooling months, energy is exchanged into the ground as a heat sink, and when the system switches to heating, the energy is recovered back from the earth.

There are several types of ground source systems, one style is installing ductwork under the ground. The ductwork style would condition the air only by temperature, equal to the ground, by flowing it through the ductwork. Additional conditioning, dehumidification and cooling/heating would need to be applied throughout the year as needed. The other is burying a closed loop pipe system. The closed loop pipe would be combined with a water source HP to exchange energy with the earth, this system would fully condition the air as needed for the season.

With water source HP combined with geothermal ground source, there are two primary ways, vertical boreholes and horizontal fields. Vertical boreholes are the more efficient system out of the two but also cost the most to install and uses more specialized equipment for the installation. For the horizontal fields, multiple methods could be used to excavate the soil to the required depth for the pipe to be installed. The horizontal field is affected by the surface temperature of the soil but maintains a greater COP than air source and is cheaper and easier to install than vertical borehole.

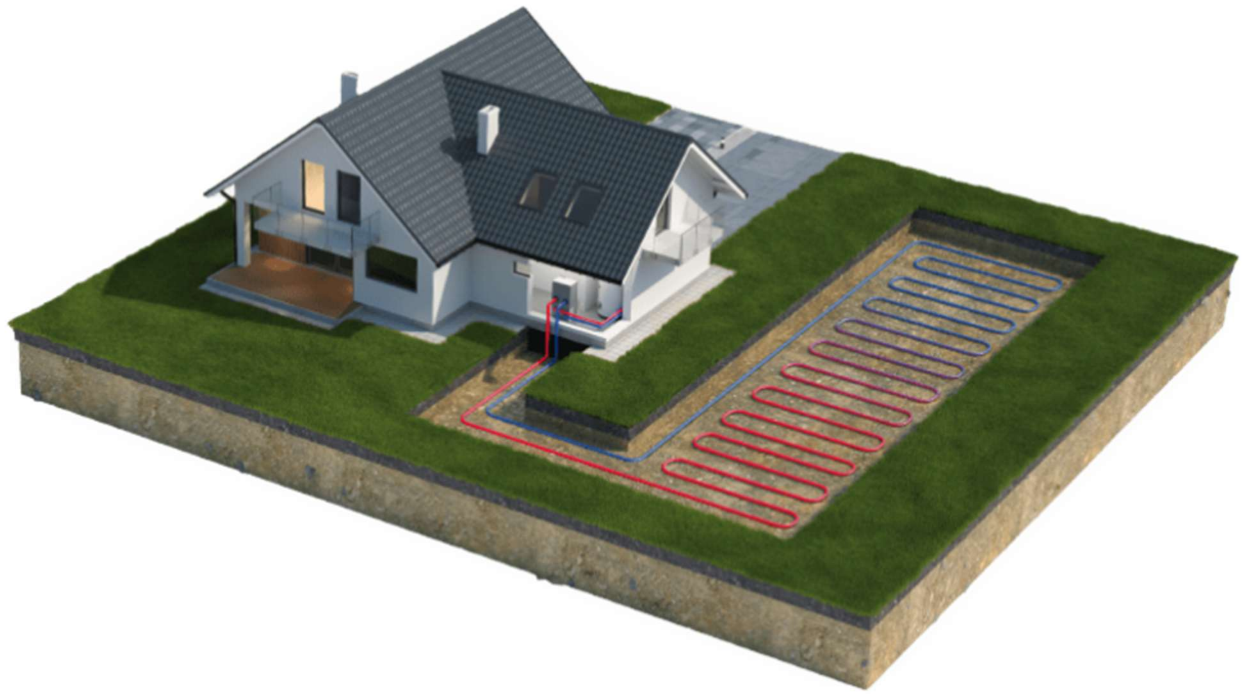


Fig. 1.2 House with horizontal geothermal field [capitalheat.com]

Figure 1.2 is a simple illustration showing how a typical horizontal geothermal system would be installed next to a house. The horizontal geothermal water source heat pump system will be one of the main subjects of this thesis.

1.2 Drain Fields of Septic Systems

A septic field, also known as a drain field or leach field, is the septic system's wastewater start of final stage for the treatment process. Wastewater leaves the septic tank and is distributed evenly into the field using buried perforated pipes in or over gravel. The wastewater seeps through the soil filtering harmful impurities and returning treated water back into the environment.

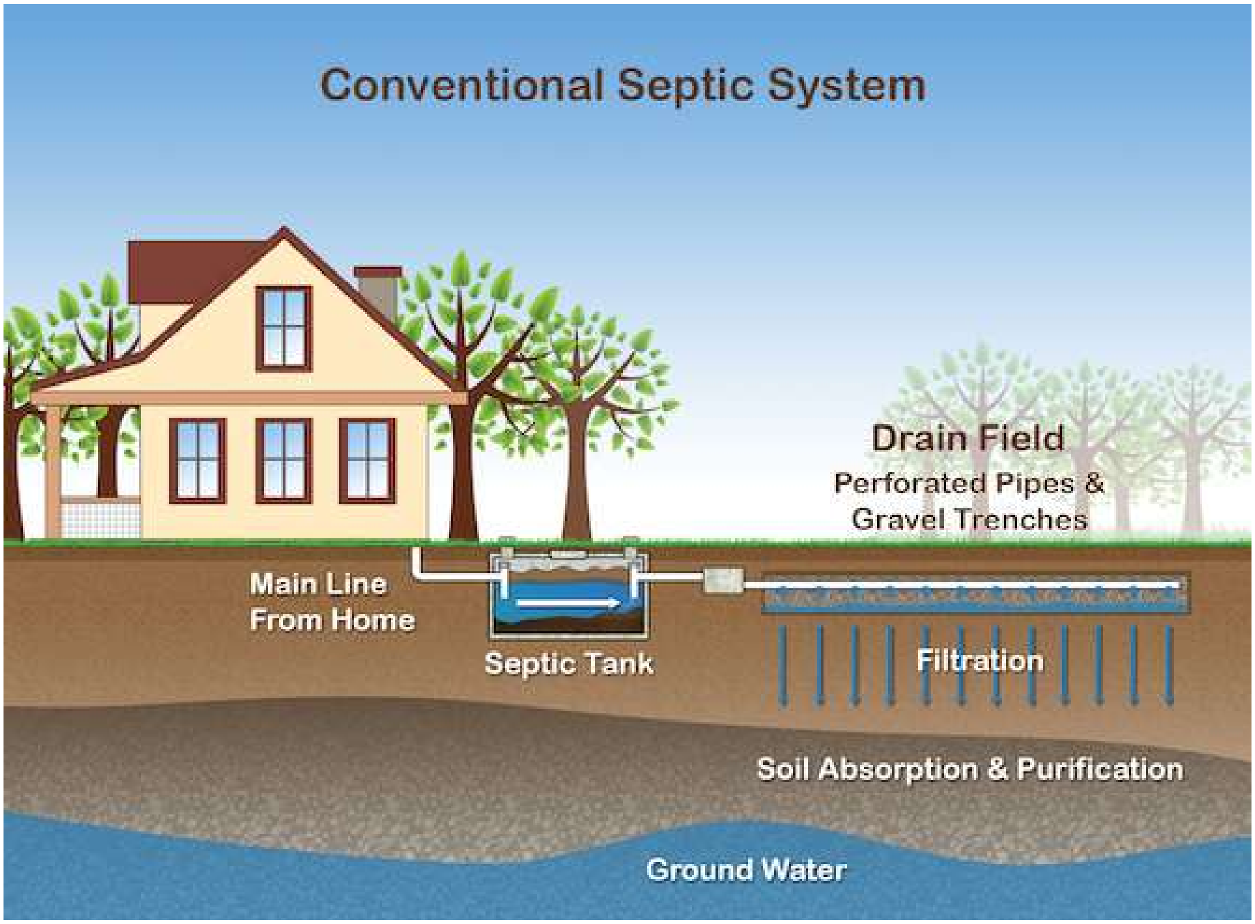


Fig. 1.3 Diagram of septic system [septicshoppe.com]

The above figure shows a simple process for the septic system of a house. Waste flows from the house into the septic tank and the excess wastewater flows out into the drain field and disperses into the ground. Which is filtered and purified by the soil before returning to the ground water. This is the second major part of this thesis.

1.3 Thesis: Enhancing horizontal geothermal system with wastewater

With the ever-increasing cost of material, labor, and energy it is important for engineers to find new ways and develop more efficient and cost-effective systems that are reliable and easy to produce. The problem with geothermal systems compared to traditional units is the significant increase in installation costs. Of the two, vertical and horizontal ground, vertical is the most efficient but has the highest installation cost and requires specialized equipment. The dilemma is how to make the horizontal ground more efficient and affordable. By solving this problem, we can provide more opportunities to save on energy consumption and reduce costs associated with better technologies.

A proposed solution is to combine horizontal geothermal and septic systems together. The geothermal field would be under the septic drain field in a layered configuration. This way, the geothermal system will benefit from the wastewater of the septic system by increasing the thermal conductivity of the soil, making the geothermal system more efficient. Additionally, the construction cost for the combined systems will be lower than if built separately.

The remaining paper includes a proof-of-concept study using known soil characteristics of Shawnee, OK and Dymola modeling software, showing the increase in soil conductivity. The design of the geothermal field with the septic system will be compared to other commonly used systems and studied with concluded details in the paper.

(a) (b)

Fig. 1.4 (a) Horizontal Geothermal Field [buildwithrise.com] (b) Septic Drain Field [CREDO]

As can be seen from figure 1.4, the footprints of each field of each system can be combined in a layered format. The research for this thesis will look at combining the two fields together and how this will change the efficiency of the geothermal water source HP system.

1.4 Outline of the thesis

The remaining of the paper will include a proof-of-concept study, using known soil and air characteristics of Shawnee, OK, and how soil properties affect conductivity. A Dymola modeling software program, showing the increase in soil conductivity. Comparison of the design to other commonly used systems. A design of the geothermal field with the septic system layered together. Cost analysis comparing the combined system with the other commonly used ones, showing the return on investment. Then final remarks showing other possible ways to achieve these results, and future research over the thesis.

Chapter 2: Soil Conductivity

2.1 What causes the change in soil conductivities

There are a multitude of factors that change the thermal conductivity of soils, this included types of soil, differentiating minerals in each soil type, depth of the soil affecting its pressure, and porosity of the soil. All these factors were studied by Lev Eppelbaum, Izzy Kutasov, and Arkady Pilchin in Applied Geothermics. They found while studying different soils, samples of the same soil would have differentiated thermal conductivity. It was understood that the samples would not be 100% identical, and so their thermal properties should differ to some degree, but they found that they would differ greatly in some experiments. Another explanation for these different and elevated values may be the varying degrees of water saturation in the samples. It is well established that samples saturated with water have much higher values of heat conductivity than dry samples [Lev et al. 2014].

The main reason for different thermal conductivity in identical dry soil is the porosity of each sample. With air having very low thermal conductivity compared to soil types, filling the gaps in the soil as in the porosity, will increase the bulk thermal conductivity of the soil.

Thermal conductivities of sediments are more a function of their water content than of their mineral constituents. Water saturated samples have higher thermal conductivity than dry samples, as water has higher thermal conductivity than air. This means for thermal conductivity λ that always: λ matrix > λ wet rock > λ dry rock. Therefore, conductivity becomes a function of porosity, or the state of compaction, as well as the mineralogy and the pore-filling fluid. [Welte et al. 1997]

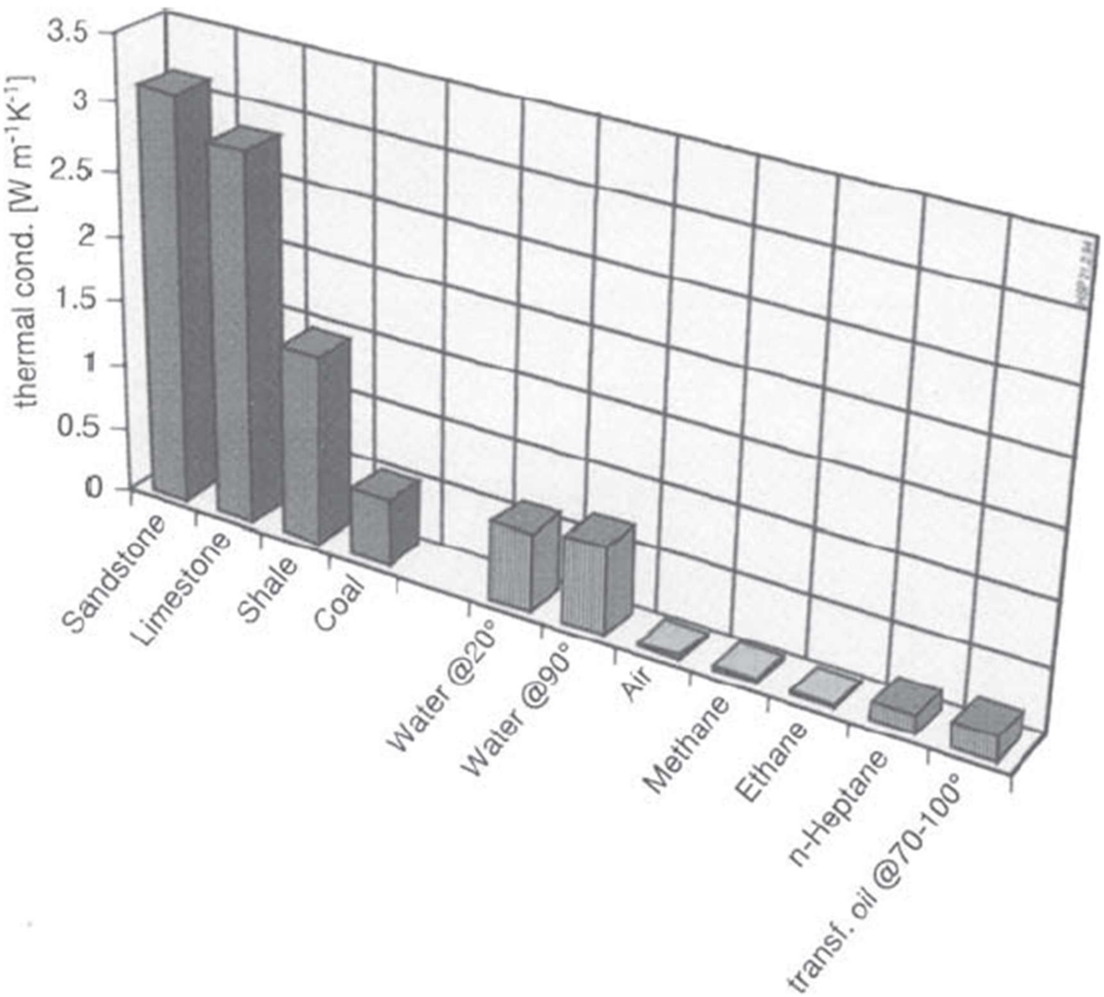


Fig. 2.1 Thermal conductivities of selected rocks and fluids. The values for rocks are matrix conductivities for 0% porosity at 20° C. (Data from IES 1993, Blackwell and Steele 1989; Clark 1966; Weast 1974) [Welte, Horsfield, Baker; 1997]

All pore-filling fluids have lower conductivity values than rocks. This causes bulk thermal conductivities to decrease with increasing porosity. In other words, bulk thermal conductivities should increase with progressing compaction. Porosity and the type of pore fluid are the most important controlling factors, as the thermal conductivity of a water saturated sediment can increase by a factor of 2 – 5 during compaction from its initial porosity value to its final value. Water has considerably higher conductivity (0.6 $Wm^{-1}\ K^{-1}$) than gas (0.03 $Wm^{-1}\ K^{-1}$), air and even oil. Therefore, we should see differences in temperature distribution depending on the degree of hydrocarbon saturation of reservoir and source rocks. Examples for the effect of porosity and different pore fluids on bulk thermal conductivity are plotted in Fig. 2.2 [Welte, Horsfield, Baker; 1997].

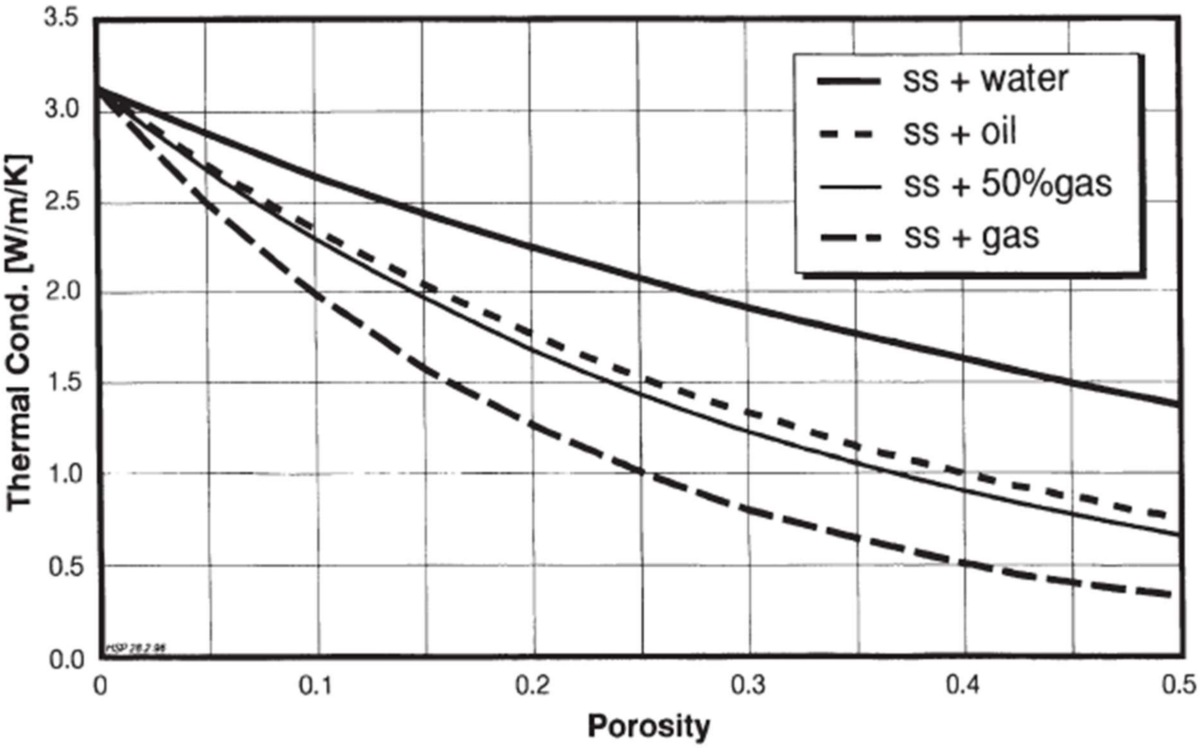


Fig. 2.2 Thermal conductivity of sandstone as function of porosity and pore fluid [Welte, Horsfield, Baker; 1997]

As can be seen in the graph, when porosity is zero thermal conductivity is the highest, it also shows using water to fill the gaps increase thermal conductivity the most. Since soil cannot be perfectly compressed, to where porosity is zero, water is the best choice to use to bring up the bulk conductivities of the soil.

2.2 Site location soil conductivity

For soil conductivity, this thesis focuses on Shawnee, OK as its location for the soil properties obtained from a case study [Hurt et al. 2025]. Local data suggests that the soil type is predominately silt/sand. The typical report of soil thermal properties in Table 2.1 (Dalla Santa et al., 2020) shows the heat conductivity coefficient of each soil and its description.

Table 2.1: Typical thermal conductivity values of different soil types [Dalla Santa et al., 2020]

	Thermal Conductivity $\frac{BTU}{hr-ft-°F}$ $\left[\frac{W}{m-K}\right]$		
Sediment category	**Min-value**	**Max-value**	**Recommended value**
Gravel dry	0.232 [0.4]	0.522 [0.9]	0.232 [0.4]
Gravel water-saturated	0.928 [1.6]	1.45 [2.5]	1.044 [1.8]
Sand dry	0.174 [0.3]	0.522 [0.9]	0.232 [0.4]
Sand moist	0.58 [1]	1.102 [1.9]	0.812 [1.4]
Sand water-saturated	1.16 [2]	1.74 [3]	1.392 [2.4]
Clay/silt dry	0.232 [0.4]	0.58 [1]	0.29 [0.5]
Clay/silt water-saturated	0.638 [1.1]	1.798 [3.1]	1.044 [1.8]
Till/loam	0.638 [1.1]	1.682 [2.9]	1.392 [2.4]
Peat, soft lignite	0.116 [0.2]	0.406 [0.7]	0.232 [0.4]

The speculated soil conductivity of the location was to be 1 $Wm^{-1}\ K^{-1}$, in testing real-world applications, the thermal conductivity is almost always different than what is hypothesis. In determining the true thermal conductivity of the soil, a thermal response test (TRT) [Gehlin 2002] was conducted on an existing geothermal borehole in the area. Figure 2.4 shows the area where the TRT was performed.

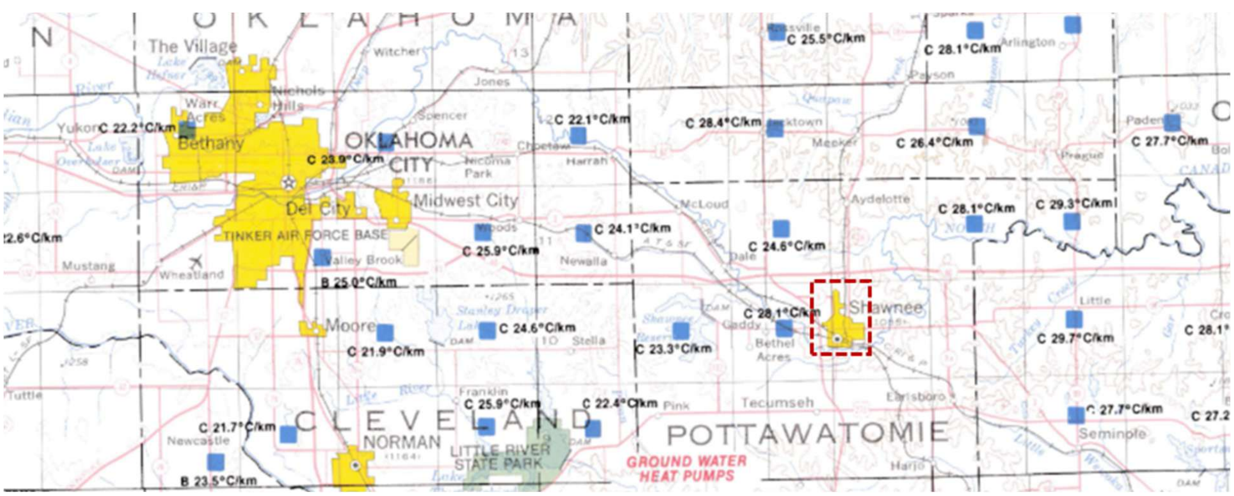


Fig. 2.3 Geothermal TRT sight location [Hurt et al. 2025]

The TRT was conducted by a third party local geothermal testing company for a 48-hour period starting January 30, 2024, resulting in a thermal conductivity of 1.7 $Wm^{-1}\ K^{-1}$, 70% higher than what was speculated. The case study for this test [Hurt et al., 2025] goes over how the TRT is performed and data calculated. The high increase in thermal conductivity from the calculated amount showed that something was affecting the thermal conductivity of the soil more than previously thought. This was determined to be underground water flow, an aquifer.

2.2.1 Soil conductivity with ground water

Using TRT data from the case study [Hurt et al., 2025], a simulation was developed to analyze the borewell's penetration into the aquifer. As soil saturation fluctuates, its thermal conductivity and heat capacity (both specific and volumetric) vary accordingly. Understanding thermal diffusivity under different fluid properties is crucial for designing systems and upscaling experimental data to real-field applications. To facilitate experimental design and upscaling, it is essential to group relevant parameters into dimensionless variables. Dimensionless numbers provide simplified models to characterize heat transfer behavior across diverse systems. In the simulation, the thermal conductivity of ground water movement in soil is analyzed using the following dimensionless parameters in heat transfer:

Nusselt number (fluid) $$Nu = \frac{hL_p}{k} \tag{1}$$

where h is the convective heat transfer coefficient (W/m²·K), Lp is the characteristic length (m), and k is the thermal conductivity of the fluid (W/m·K), ground water.

Prandtl number $$Pr = \frac{\mu C_p}{k} \tag{2}$$

where μ is the dynamic viscosity of the fluid (Pa·s), Cp is the specific heat capacity at constant pressure (J/kg·K) and k is the thermal conductivity of the fluid (W/m·K).

Biot number (rock) $$Bi = \frac{hL_p}{k} \quad (3)$$

where h is the convective heat transfer coefficient (W/m²·K), Lp is the characteristic length (m), and k is the thermal conductivity of the solid (W/m·K), rock/soil.

Reynolds number $$Re = \frac{\rho V \;\; p}{\mu} \quad (4)$$

where ρ is the fluid density (kg/m³), V is the characteristic velocity of the fluid (m/s) ground water flow, Lp is the characteristic length (m) of the pipe exposed to the flowing ground water, and μ is the dynamic viscosity of the fluid (Pa·s). These parameters provide a framework for characterizing heat transfer behavior in saturated soil and enable the translation of laboratory findings to field-scale applications. These parameters are critical in both experimental design and real-world applications.

The dimensionless numbers are used in designing numerical simulation cases. For example, Nusselt number is = total heat transfer / (conductive heat transfer), which involves three physical quantities: convective heat transfer coefficient, characteristic length, and thermal conductivity. Simulating changes for every parameter would result in an impractical number of cases, so a selective approach was taken. If the Nusselt number is the same, their impact on heat transfer efficiency will be the same. In this example, increasing the convective heat transfer coefficient vs decreasing the length of well exposing to the aquifer would give you the same effect. In reservoir simulation, it will be much easier to change the convective coefficient rather than changing the length.

Table 2.2: Simulation data from TRT

Groundwater flux, m/D	Equivalent Thermal Conductivity, W/(m-K)
0	2.801
0.025	3.125
0.0375	3.356
0.05	3.542
0.075	3.935
0.1	4.253

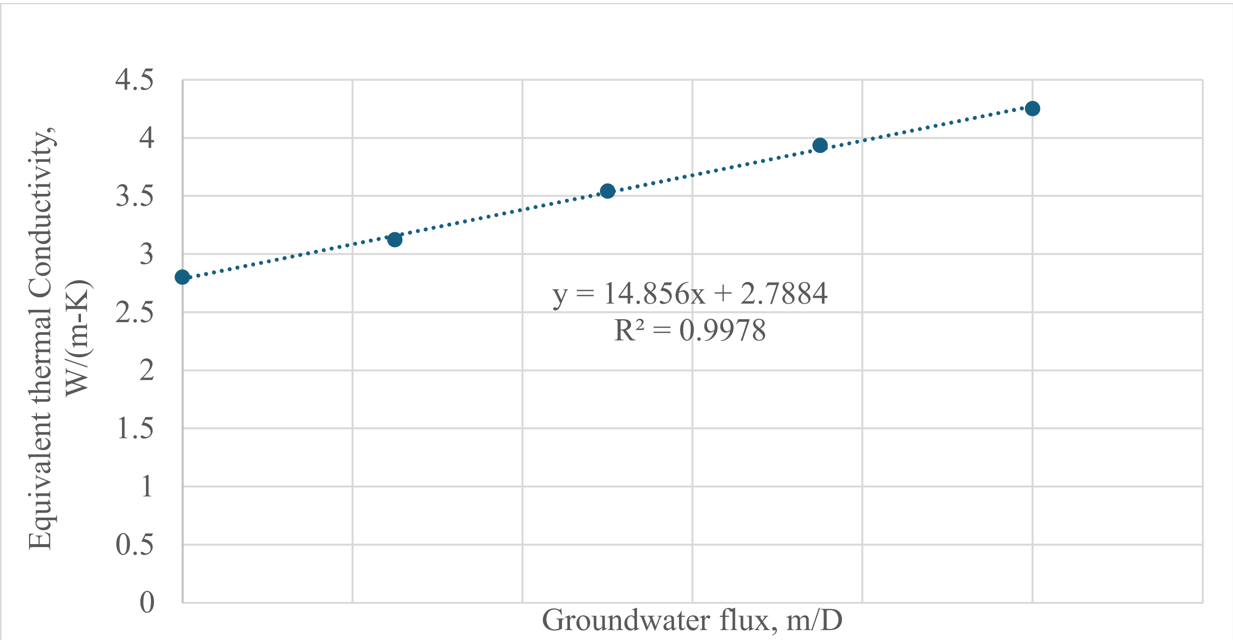


Fig. 2.4 Plotted simulation data from the TRT

From the simulation, it was found that with an increase in groundwater flux, meter/day flow of water through soil, there was an equivalent thermal conductivity increase of the system. The developed simulation showed this; after collecting the data and plotting, it showed a linear relationship. The plotted graph was $y = 14.856x + 2.7884$ with $R^2 = 0.9978$. The saturated water value was from the numerical regression of the data from the TRT, as shown in table 2.2.

2.3 What effect does this have on a geothermal system

The thermal efficiency of a geothermal heat pump is highly affected by the thermal conductivity coefficient of the soil in contact with the wellbore. The thermal conductivity coefficient is affected by soil minerals, void ratio, in-situ fluid flow condition, and moisture contents [Hurt et. al., 2025].

With the understanding of saturated soil increasing the heat transfer, this is what led to the initial development of the idea for this thesis.

The known soil properties in Shawnee, OK produced a thermal conductivity of 1 $Wm^{-1}\ K^{-1}$, for a single geothermal borehole. After testing an existing borehole, it was found that it had an actual conductivity of $1.7\ Wm^{-1}\ K^{-1}$, this would be used for the vertical borehole system. In the groundwater simulation, numerical regression of the TRT data produced a thermal conductivity of saturated soil to be $2.8\ Wm^{-1}\ K^{-1}$, this will be used to simulate the added wastewater to the horizontal geothermal field.

With this information, the idea was developed on how to add water to the soil to increase thermal conductivity, but without adding cost to the geothermal system. So, it was hypothesized that using an existing source of water, wastewater from the septic system, would achieve this objective without increasing the cost.

To investigate the impact of increased groundwater flux—the movement of water through soil—on the thermal conductivity coefficient, this thesis assumes saturated soil conditions with intermittent septic wastewater releases. This is the source idea on how to simulate and compare different heat pump HVAC systems.

Chapter 3: Simulation

To simulate horizontal geothermal with an increase in thermal conductivity and compared to a vertical borehole and ASHP systems, the modeling software Dymola 2024x using Modelica language was used. The main reason for using Dymola was because it had a large library of built-in systems for geothermal and heat pumps. This thesis used the Buildings-v11.0.0 library (Modelica Buildings Library).

3.1 Modelica Building Library

The Modelica Buildings library is a free, open-source tool offering dynamic simulation models specifically designed for building and district energy and control systems. Its primary purpose is to provide a flexible and efficient platform for modeling the design and operation of both new and existing energy and control systems across buildings, districts, and data centers. This library is particularly suited for rapid prototyping and in-depth analysis of energy and control systems, risk reduction through integrated energy systems testing, and the development, specification, verification, and deployment of controls within a model-based design framework. Additionally, it supports the operational analysis of existing building systems and facilitates the export of digital twins for functional testing, control sequence verification, energy optimization, fault detection, and diagnostics.

The library includes an extensive array of models covering HVAC systems, various energy storage solutions such as water and ice tanks, boreholes and borefields, phase change materials (PCM), and batteries, as well as control systems, including a reference implementation of ASHRAE Standard 231P. It also features models for heat transfer between rooms and the exterior, which can be implemented natively in Modelica with either detailed or reduced-order models, or through integrated runtime coupling with EnergyPlus (also known as Spawn of EnergyPlus). Furthermore, the library provides tools for modeling multizone airflow, natural ventilation, contaminant transport, single-zone computational fluid dynamics coupled to heat transfer and HVAC systems, and data-driven load prediction for demand response applications. It also encompasses electrical systems for both DC and AC circuits, including balanced and unbalanced two- and three-phase configurations. Lastly, the library includes comprehensive system and template models for HVAC systems, district energy systems, and data center cooling systems, making it a versatile resource for energy systems design and operation. [Modelica Buildings library]

3.1.1 Buried Pipe

The Buildings.Fluid.FixedResistances.BuriedPipes model in the Modelica Buildings Library is specifically designed to simulate the thermal interaction between buried pipes and the surrounding soil. It is particularly useful for district heating and cooling applications. The model incorporates potential flow theory and the "mirror-image" method for calculating heat transfer between the pipes and the ground. This approach was extended to accommodate multiple pipes. By simulating the steady-state heat transfer process, the model assumes homogeneous and isotropic soil properties, treating both the ground surface and the pipe exteriors as isothermal planes. The heat transfer is radial, with no axial diffusion included in the calculation.

Key parameters in this model include the number of pipes and axial segments, soil thermal properties, climatic conditions, and pipe geometry—such as length, depth, and radius. Its flexibility allows for analyzing complex underground piping systems and optimizing their design. The model supports applications with multiple pipes, axial segmentation, and varied configurations, making it ideal for efficient energy transfer in district systems. With these capabilities, users can evaluate the thermal performance of buried piping networks and make data-driven decisions to enhance their operation. [Modelica Buildings library]

3.2 Designing horizontal simulator

Dymola has built-ins for a vertical geothermal borewell, or even a field of borewells, but does not have one for horizontal geothermal systems. So, a horizontal system needed to be designed, luckily, Dymola has a ground coupling function, figure 3.1 below, which would work for a horizontal pipe in the ground. Dymola pathway:

Buildings.Fluid.FixedResistances.BuriedPipes.PipeGroundCoupling

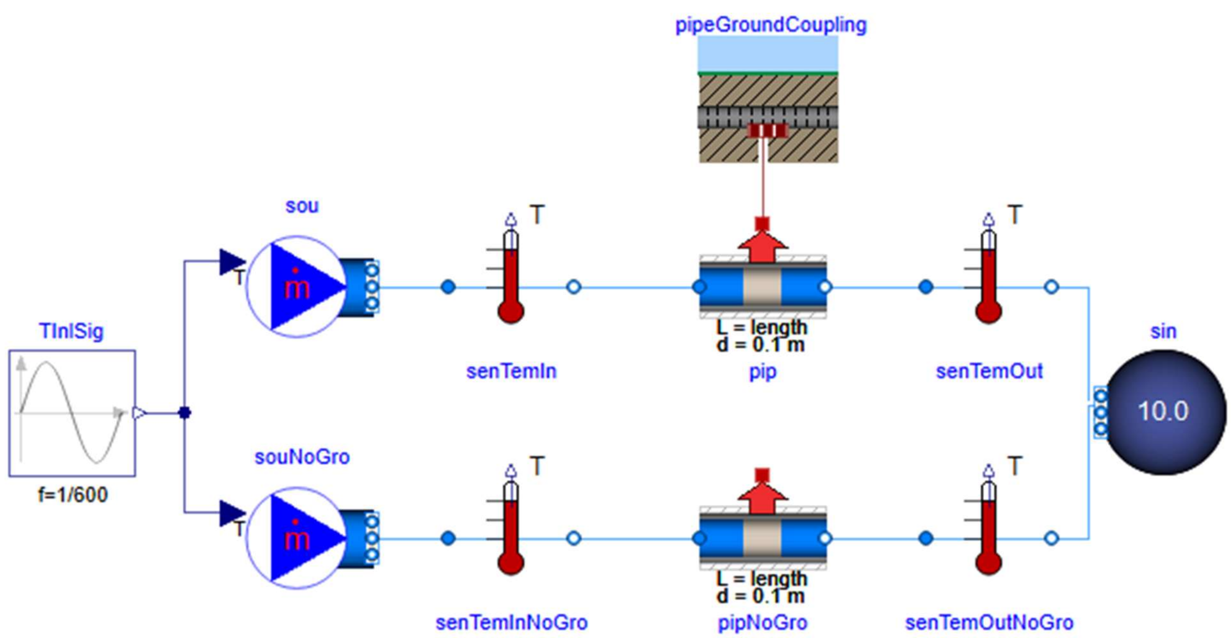


Fig. 3.1 Dymola Pipe Ground Coupling Example

Dymola's existing ground coupling example functions the same as a horizontal geothermal system. The Dymola's example is a simple way of showing and comparing how energy is exchanged with the ground in the program. This function is a simulation that shows the fluid temperature difference passing through buried pipe and unburied pipe. The simulation was modified to only focus on buried pipe, as can be seen in figure 3.2.

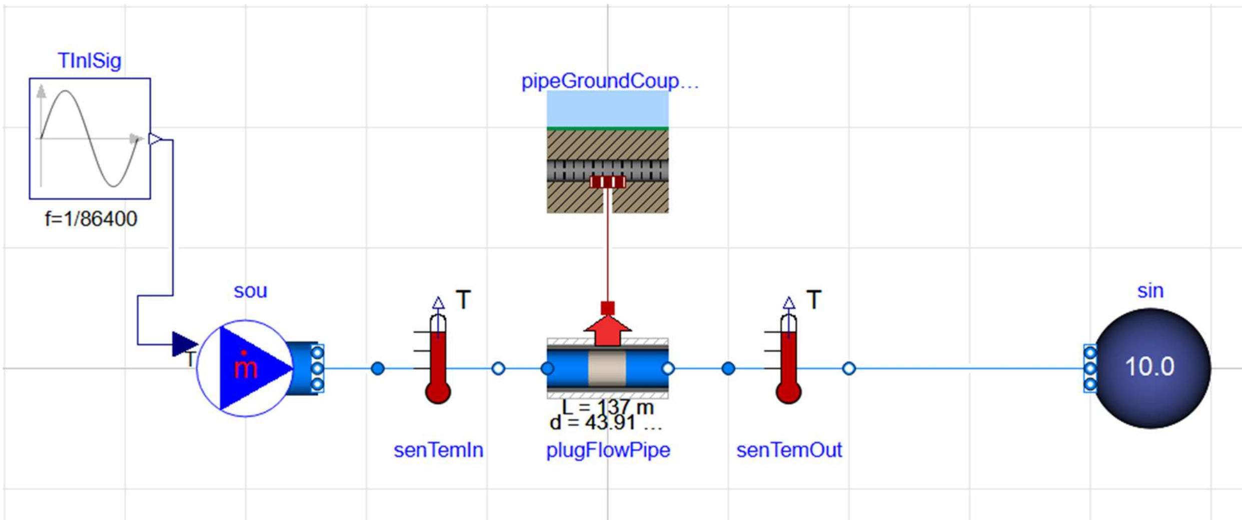


Fig. 3.2 Dymola Pipe Ground Coupling Example Modified

With the modified function, the first simulation test, this was to prove that Dymola can simulate a horizontal system. The (TInlSig) sends a signal changing the inlet temperature of the fluid flowing through the pipe. The (sou) is a pump, all parameters were left as default, only the flow rate was changed. The flow rate was set as fixed and the rate was brought in from the TRT case study [Hurt et al., 2025] information. The pipe (plugFlowPipe) parameters also came from the case study [Hurt et al., 2025]. The (pipeGroundCoupling) is the soil that the pipe would be buried in, the soil parameters were left as default, except for the depth of the buried pipe, set as 3m. The depth was picked to keep the water from freezing and the parameters being changed come from the case study [Hurt et al., 2025]. Though the case study was for a vertical borewell, its piping is similar to horizontal, and this first simulation was used to prove it would work as a horizontal system. The temperature sensors (sen Temin/out) just tell the inlet and outlet fluid temperature of the pipe. The (sin) is an "empty void", the programing sees it as somewhere to continuously send something.

After confirming the ground coupling function in Dymola can work the same as a horizontal geothermal field, a second simulation test was designed to more accurately represent a geothermal system for a building. As shown in figure 3.3, more realistic simulation.

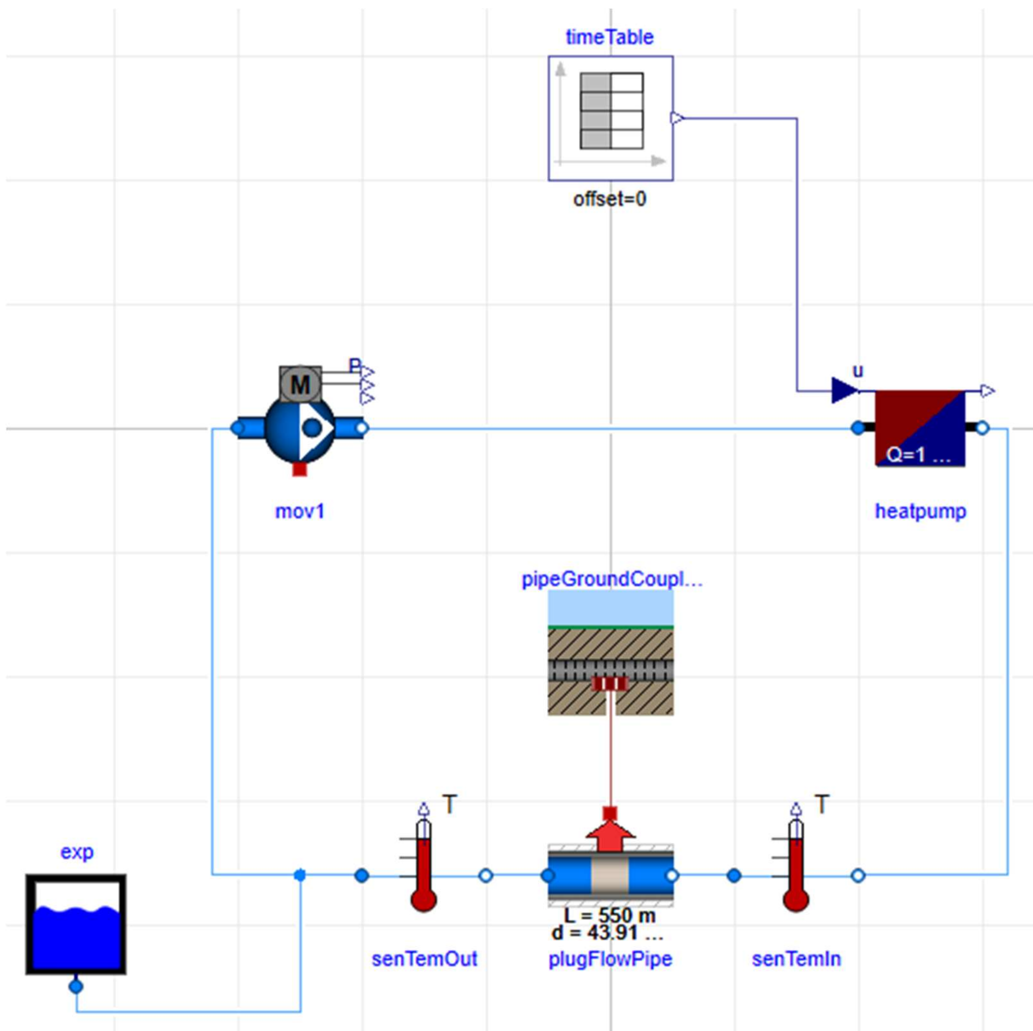


Fig. 3.3 Simulation with simulated load

The second simulation test is more of an accurate example of a closed loop geothermal system. The (timeTable) sends a signal to the (heatpump) to adjust it to kilowatts either with a positive number, adding heat to the fluid, or negative, taking heat from the fluid. The value coming from the (timeTable) with conjunction to the (heatpump) was to mimic a house 12kW heating and cooling system designed from simulated Shawnee housing unit [Hurt et al. 2025 (In Review)] for one calendar year and the (heatpump) changed it into kW for the system.

The (mov1) is a pump set at constant flow, to make the simulation simpler, calculated for the required 12kW system and parameters of the pipe. (exp) is the expansion tank for the system, as the simulation becomes more complect, the program starts to require functions like the expansion tank that would be on a real fluid pumping system. The rest of the components are the same as the first simulation test, what changes in them, are some of the parameters.

Parameters were developed using information from Shawnee, OK included but not limited to local outdoor temperature, borehole information, simulated living unit configuration, thermal loads, soil properties, and much more. All this information was used in the modeling software to simulate a 1600 sq-ft. home with an occupancy of 4.

The fluid was changed to a propylene glycol water mix, this was because its temperature was going to/below the safety point of 4°C, which would cause an error in the program. A mix of 40% glycol mass fraction was selected, this is what the library had for availability. The soil properties in the (pipeGroundCoupling) were changed to match that of Shawnee, OK [Hurt et al. 2025]. The soil surface temperature was developed from [Mesonet.org]. The (plugFlowPipe) parameters were left the same except for the length, it was changed to commonly used length per ton, about 600 ft of pipe per ton of cooling, this is just a rule of thumb used by contractors.

For the final simulation, a more realistic version was designed. It would use a more accurate building design for the loads, see figure 3.4.

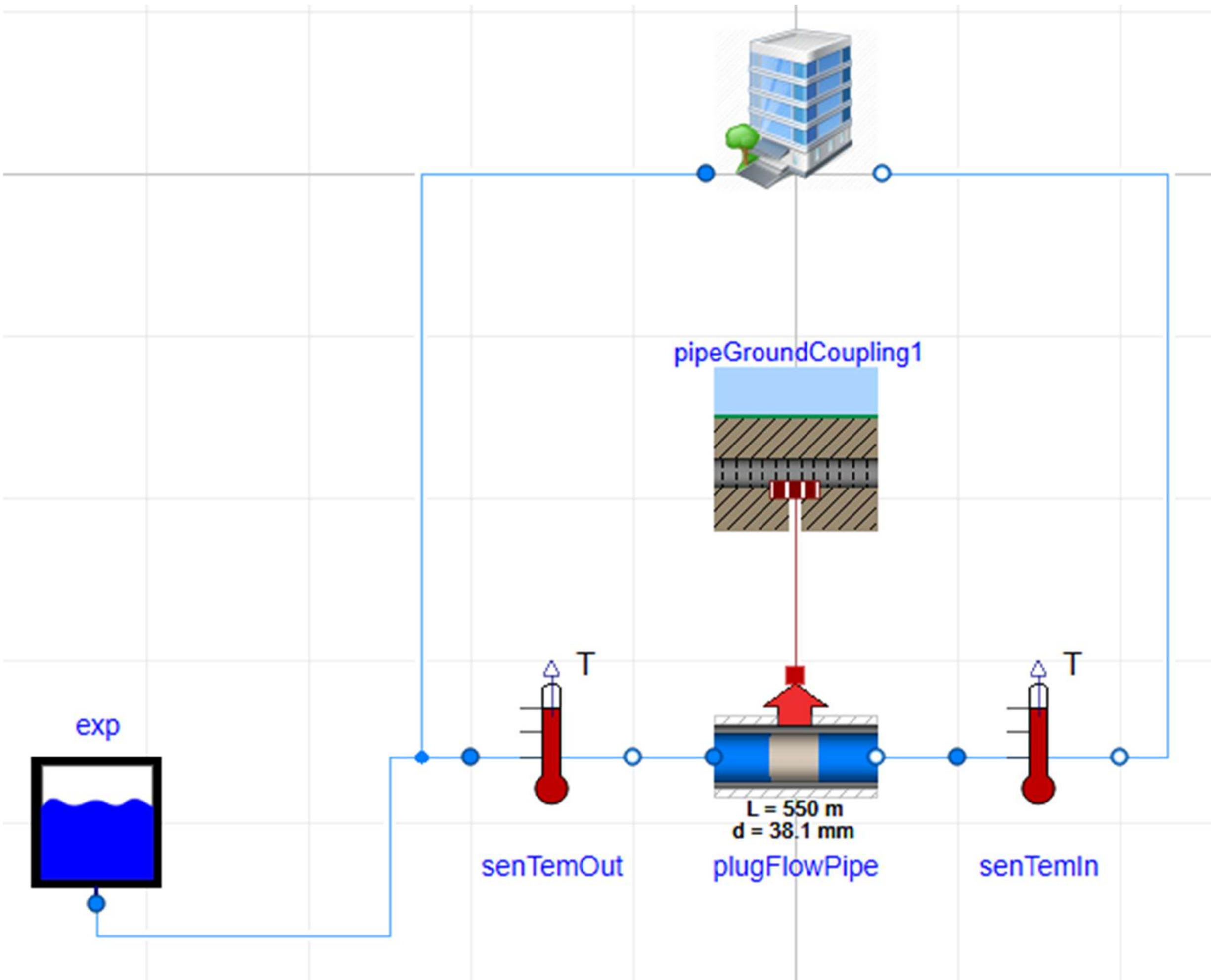


Fig. 3.4 Final simulation design

The biggest difference between the second simulation and the final is that all the components were moved into the building unit function, its details will be discussed in figure 3.5. The parameters for the (pipeGroundCoupling1) and (plugFlowPipe) will also be discussed later, these were changed to simulate a more accurate horizontal geothermal system with the saturated soil around the pipe.

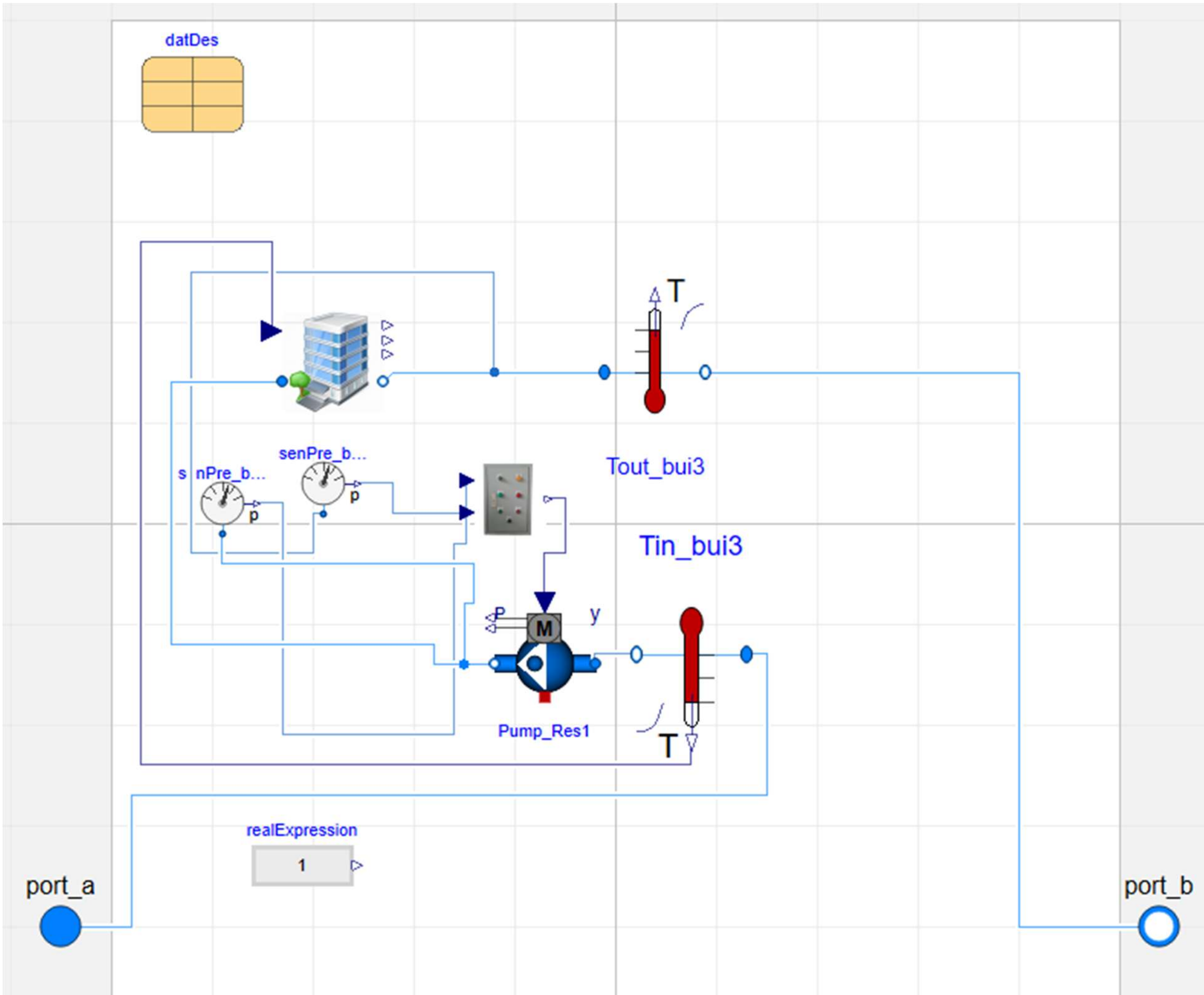


Fig. 3.5 Building unit function

This building unit function was designed to represent an actual housing unit in Shawnee, OK, full details will be supplied in the appendix. As for a real housing unit, there would be a mechanical room or space to house all the components needed for a geothermal system, besides what's outside. Fluid flows into (port_a) for the house and back out (port_b) to the geothermal field. For the heat exchanger function, using similar image as the building function, will be discussed next and shown in figure 3.6.

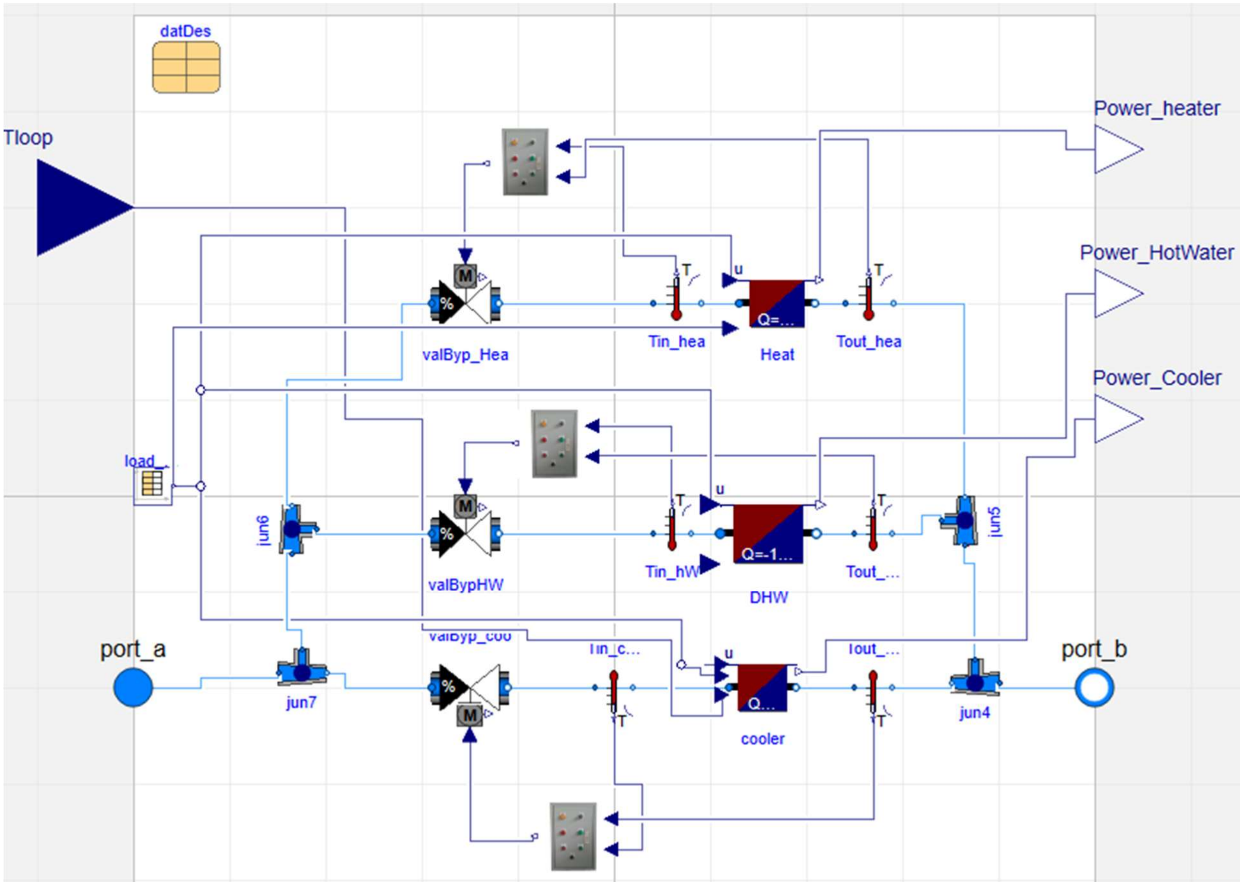


Fig. 3.6 Heat exchanger function

The heat exchanger function was designed for multipurpose simulations, it could send the fluid to what the system called for, heating, cooling, or hot water. For this thesis simulations, the hot water was ignored and turned off in the heat exchanger function by not inputting any data for it. The function would work by what signal was sent to it, either turning on the cooler or heater, sending the fluid to correct heat pump for what the load was. The loads were developed from historical temperature data of Shawnee, OK and the simulated housing unit [Hurt et al. 2025 (In Review)]. Another part of the heat exchanger function is that it would give the COP of the heating and cooling systems, this will be discussed and used later chapters.

The vertical borehole simulator uses the same building function as the horizontal geothermal simulator and will be discussed in that section, same as the ASHP simulator.

3.2.1 Horizontal parameters

At first the only parameters to change compared to the previous simulations was the size of the geothermal piping to match horizontal system sizing. While running simulations on the first versions, changing the soil conductivity, the fluid temperature would fluctuate in accordance with the conductivity, this was always the theory to what would happen. For the final simulation, during testing of different soil conductivity the fluid temperature would change, just as in the other simulations. This is when, it was noticed, that the temperatures were diverging towards the surface temperature, a result that pushed the system to be more comparable to an ASHP and not the desired temperature range of geothermal. The reason for this was because the soil's conductivity as a whole, was changed to one value, and not as a separate zone as was attended. This problem proved that higher soil conductivity meant higher heat transfer to the fluid of the system, because it was affected more by the surface temperature, and so the soil would become closer to the outdoor temperature. To fix this problem parameters were adjusted in the piping and soil functions to mimic the saturated soil zone around the pipe, seen in figure 3.7.

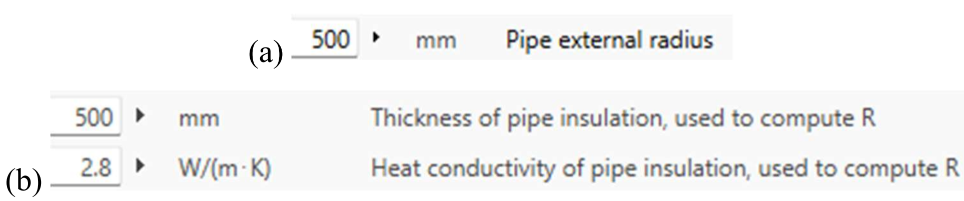


Fig. 3.7 (a) Ground coupling function parameter (b) pipe function parameters

One of the parameters inside the pipe was insulation, normally this is kept small as will be seen later, in this situation it was changed to simulate the saturated soil around the pipe. In the soil parameter, the radius was changed to facilitate the thicker insulation as simulated saturated soil. Figure 3.8 illustrates how the program would see the interaction between the soil and pipe with thicken insulation.

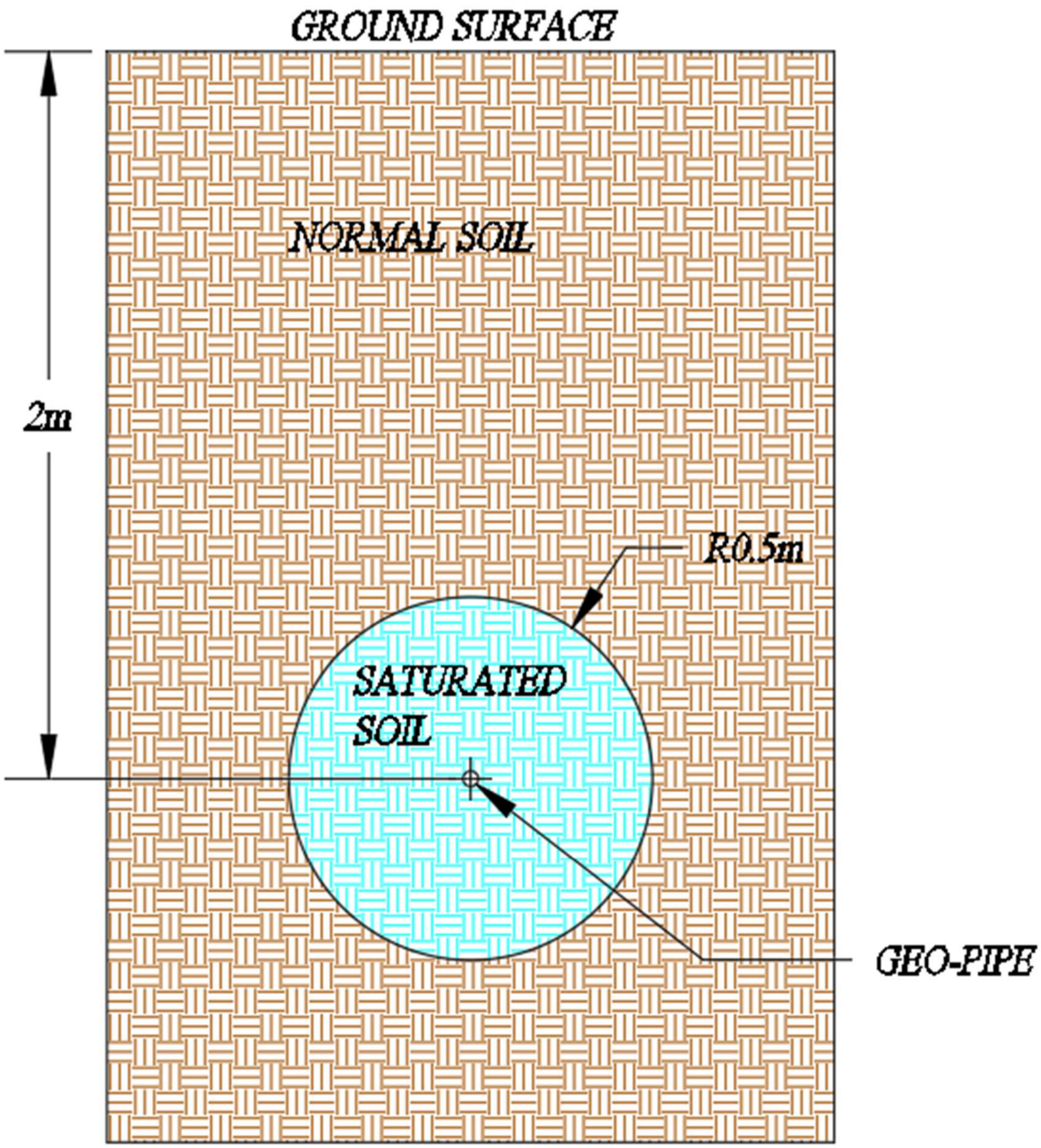


Fig. 3.8 Visual of simulation with saturated soil zone around pipe

The ground coupling function can be modified, this will be discussed in the conclusion chapter. For this simulation, changing the insulation to act as the saturated soil, as seen in figure 3.8, worked as desired. It helped with heat transfer from the fluid to the soil and stopped the surface temperature from affecting deep down into soil as before when the entire soil conductivity was the same.

For the other parameters of the ground coupling, the soil, they were changed to match the site location of Shawnee, OK, as shown in figure 3.9.

Fig. 3.9 Ground coupling function parameters

The soil is set at what the speculated properties of the site location are. The pipe length and depth were set at what is common practice in horizontal geothermal systems, this is to best mimic what a contractor would build in the real-world.

For the pipe parameters, as seen in figure 3.10, they were based on common pipe sizing and characteristics for horizontal geothermal systems [IGSHPA, 2017].

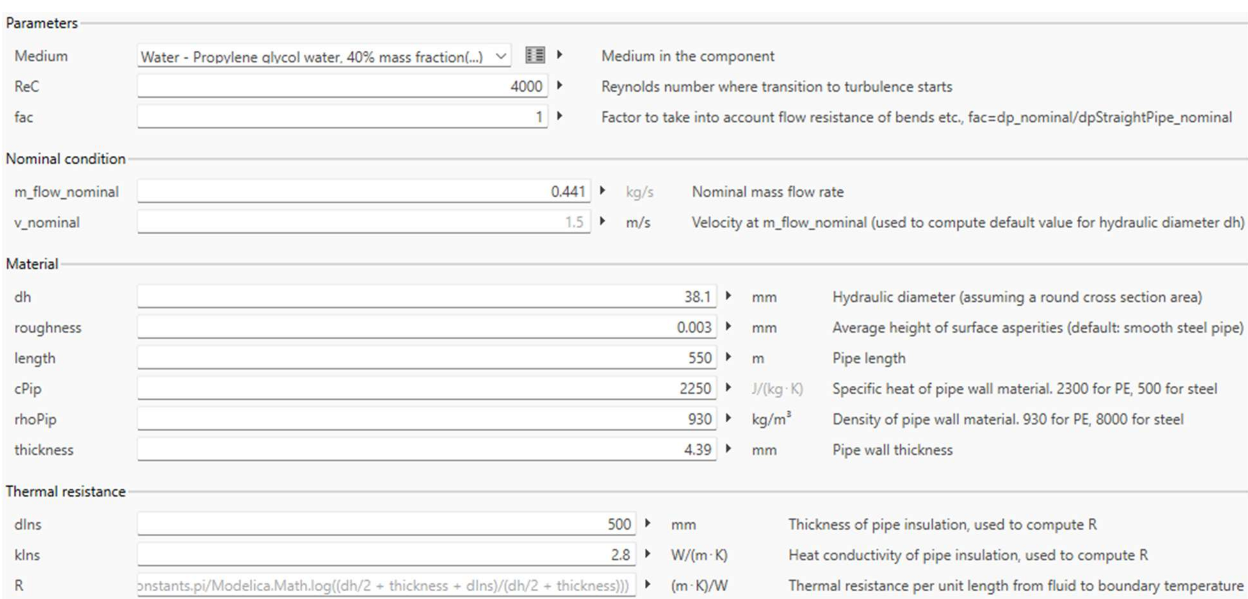


Fig. 3.10 Pipe function parameters

The piping selected is commonly used Polyethylene (PE), based on pipe diameter of 1.5" and wall thickness D11. As mentioned before, the pipe insulation was adjusted to simulate saturated soil but is usually left at 0.001mm and default conductivity, to not affect the heat transfer of the system. The insulation cannot be set to zero, or it would produce an error in the program.

3.2.2 Simulation Heat Pumps

The heat pump function in the Modelica Buildings Library, version 11.0.0, is part of a comprehensive suite of dynamic simulation models created for building energy and control systems. This library offers a variety of templates and models specifically designed for HVAC systems, including heat pumps, which efficiently transfer heat between spaces or systems. By incorporating detailed simulations, the library allows users to study the behavior of heat pumps under diverse conditions, covering both heating and cooling modes.

These heat pump models can be seamlessly integrated into larger systems, such as district heating and cooling networks, or used in standalone applications as in housing units that were used in this thesis. The library facilitates detailed modeling of heat transfer, fluid flow, and control sequences, which is instrumental in analyzing and optimizing the performance of heat pumps across different scenarios. With its specialized features, the library provides a powerful toolset for professionals seeking to enhance energy efficiency and system design.

3.3 Compared simulations

As mentioned before, this thesis wanted to compare the new horizontal design with commonly used systems. This next subchapter will be about vertical geothermal and ASHP simulations.

3.3.1 Vertical geothermal

The vertical geothermal simulation used the same functions and loads as the horizontal with only changing the ground source function to a vertical borehole, as seen in figure 3.11.

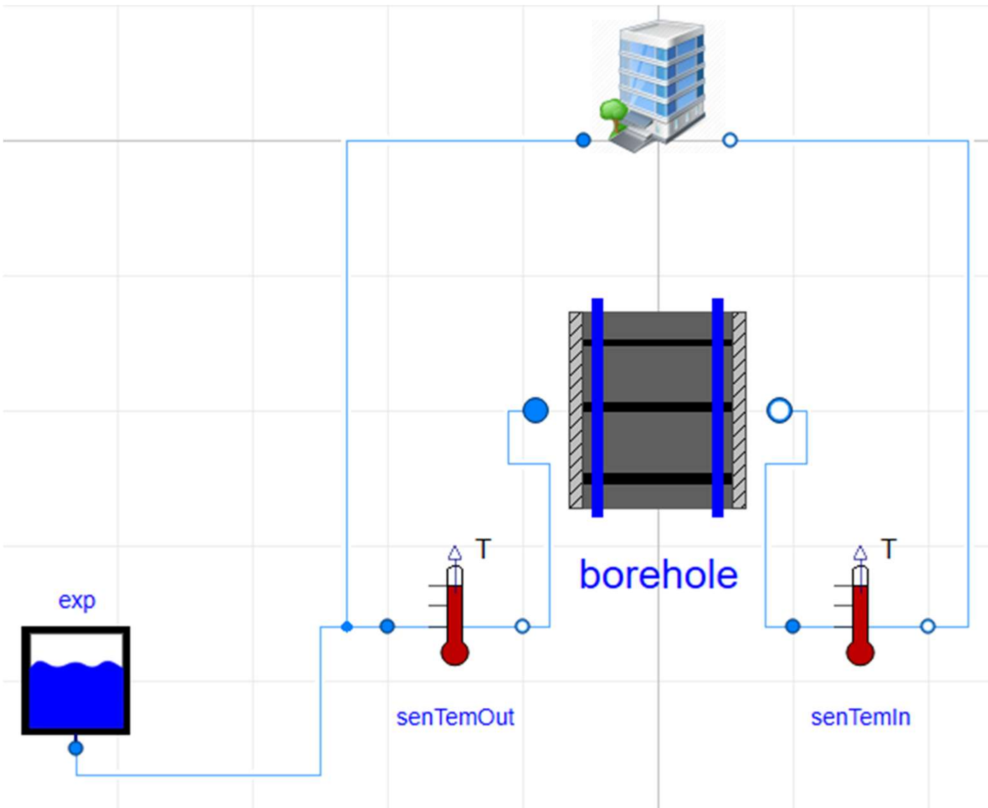


Fig. 3.11 Vertical geothermal simulation

As can be seen in the figure before, only the horizontal pipe was changed to a borehole one, this will allow for a good comparison of the two systems. The parameters were based on the case study [Hurt et al., 2025] and are shown in figure 3.12.

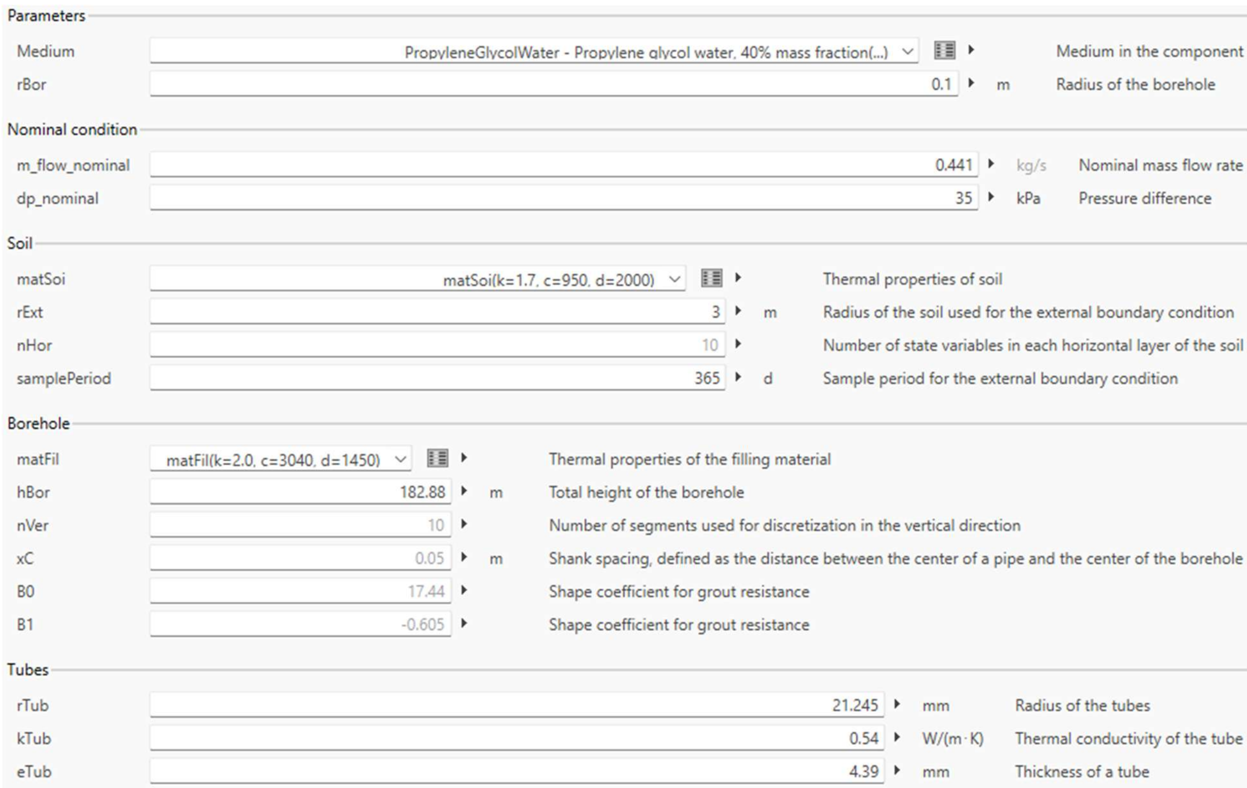


Fig. 3.12 Borehole parameters

These parameters are based on an existing vertical geothermal system with the depth been changed for the building unit been simulated. This is real-world information that will give this thesis a better data set to compare it to.

3.3.2 Air source heat pump (ASHP)

The ASHP simulator was designed to compare it with like systems, the only difference to it and the other two systems are that the other two are water source heat pumps using ground source geothermal. All the systems were designed using the same loads and tonnage for heating and cooling. Figure 3.13 shows how the ASHP simulation was designed.

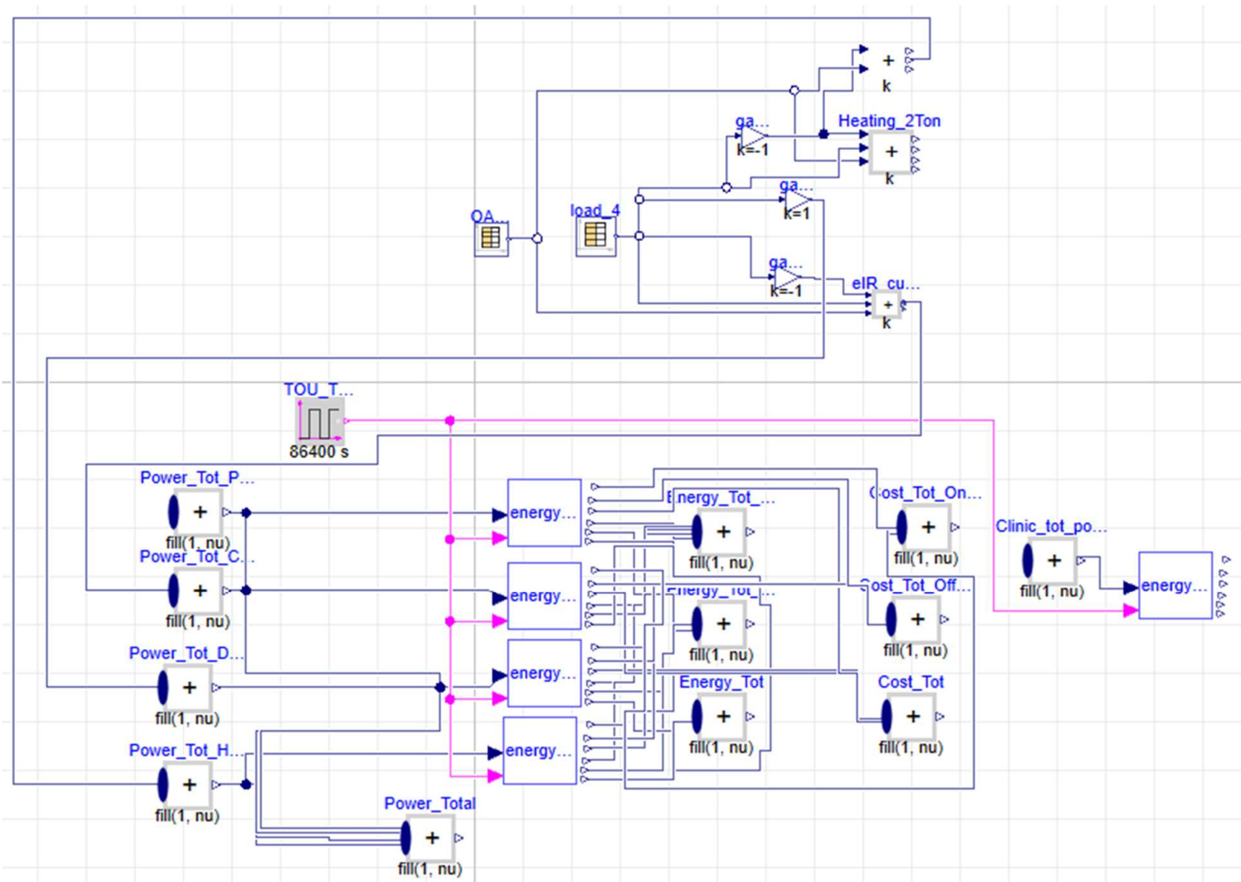


Fig. 3.13 ASHP simulation

The ASHP simulation was originally designed for multiple systems to be connected to it, for this thesis, all but the housing unit were removed to simplify the program. The only inputs the system needs are the outdoor air temperature and loads on the housing units, which are the same as used in the other simulations.

3.4 Simulation remarks

With all the final simulated systems using the same data and characteristics it will produce quality data to compare all three too.

Chapter 4: Simulation Results

This chapter will be going over the results from the simulations for the primary focus of this thesis, all other simulation results will be available in the appendix. The simulation was run as a full calendar year, starting January 1st to December 31st, full details will be in the appendix.

4.1 Horizontal system comparing soil conductivity

First the thesis wanted to show that the saturated soil zone would produce a better temperature range for the system compared to unsaturated soil. The horizontal simulation was run with the modified soil zone of a conductivity of 2.8 $Wm^{-1}\ K^{-1}$ and an unmodified soil conductivity of 1 $Wm^{-1}\ K^{-1}$.

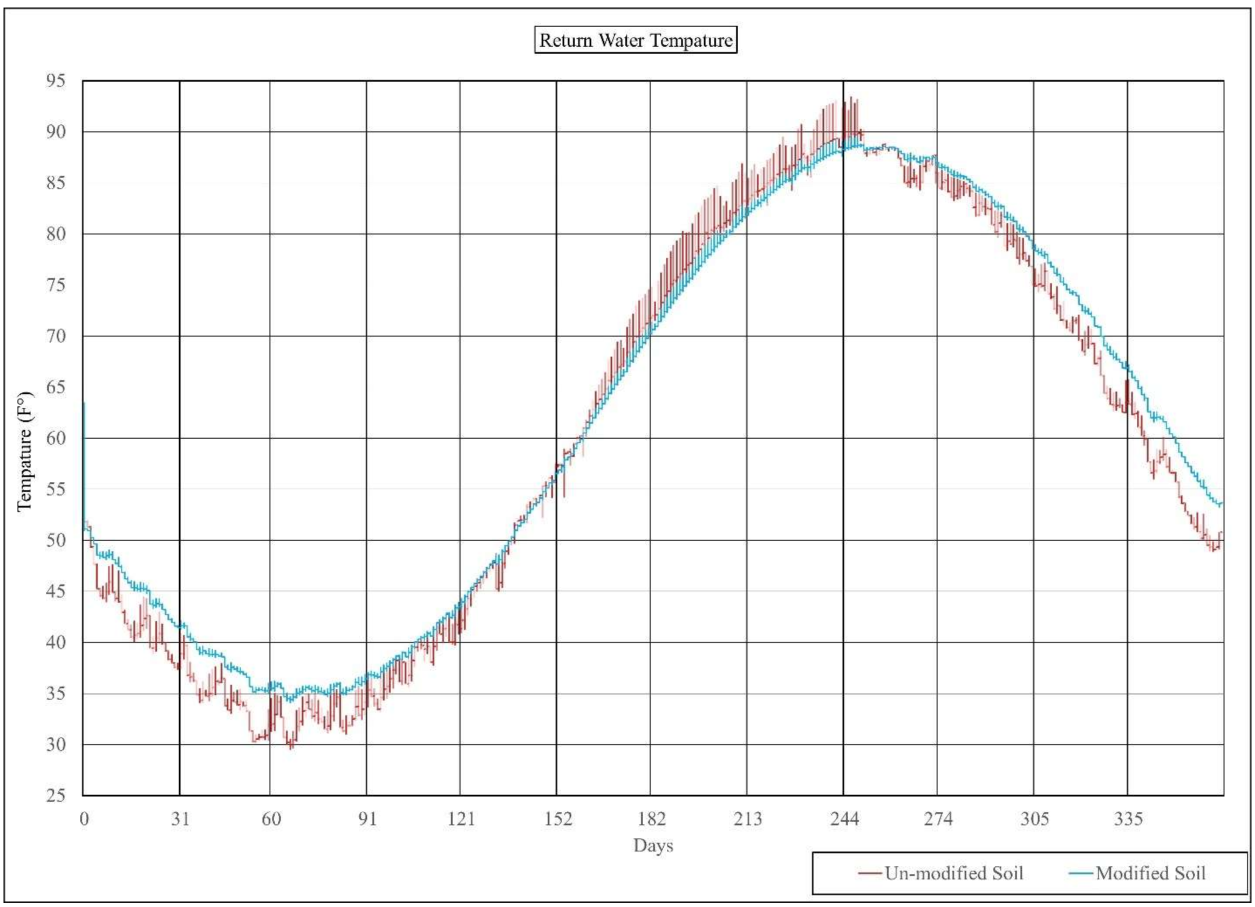


Fig. 4.1 Normal soil Vs. saturated soil, water temp. return from horizontal field

As can be seen in the graph before, the saturated soil water temperature amplitude becomes smaller and brings it closer to the more efficient range. This was the first indication that the thesis design was more efficient than the original horizontal geothermal system.

After comparing the temperature, to get a more accurate efficiency comparison, the COP of the two different soil types was analyzed. Figure 4.2 and 4.3, seen below, are the simulated COP cooling and heating respectively of each soil type.

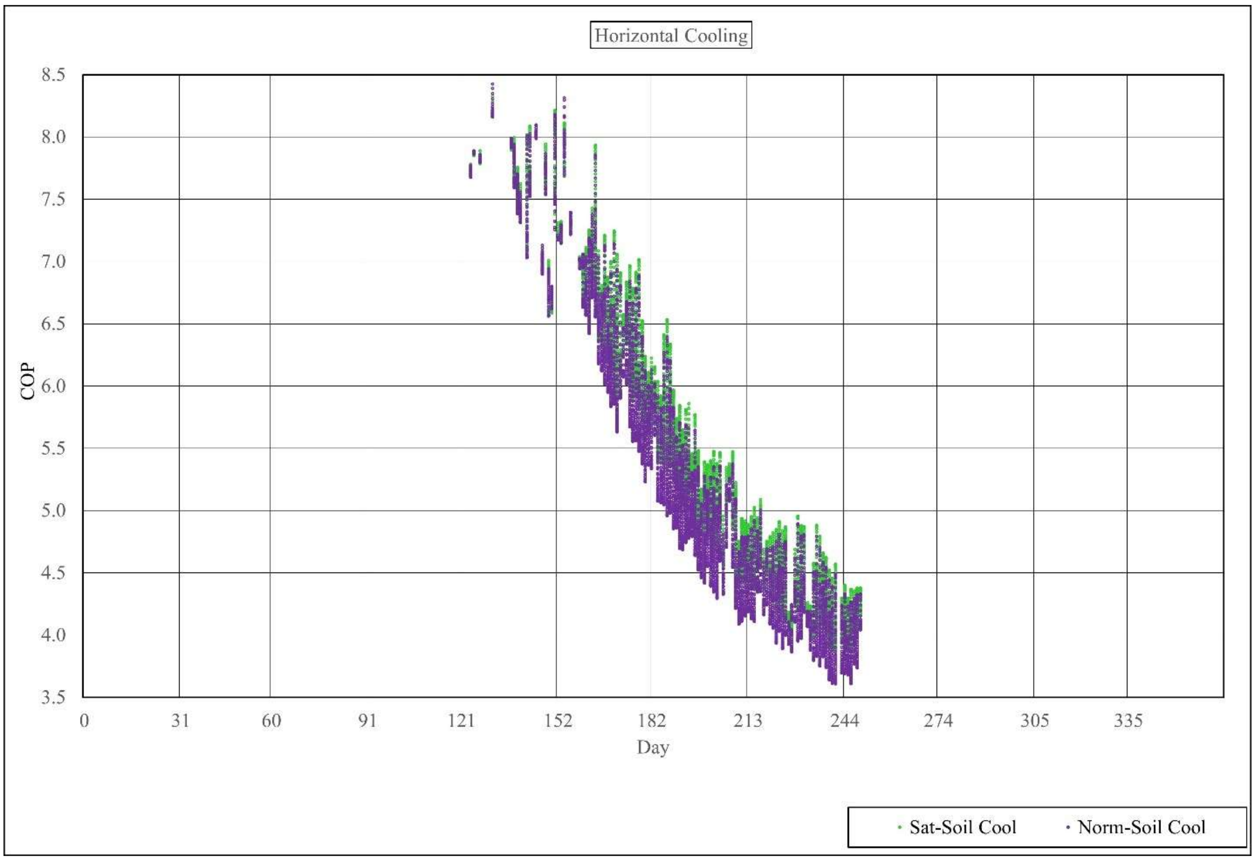


Fig. 4.2 Horizontal cooling COP comparison

During the cooling months, the saturated (modified) soil COP on average is better than the normal (unmodified) soil, this matches with the different temperature range the two systems run at. Now to compare the heating COP of the systems.

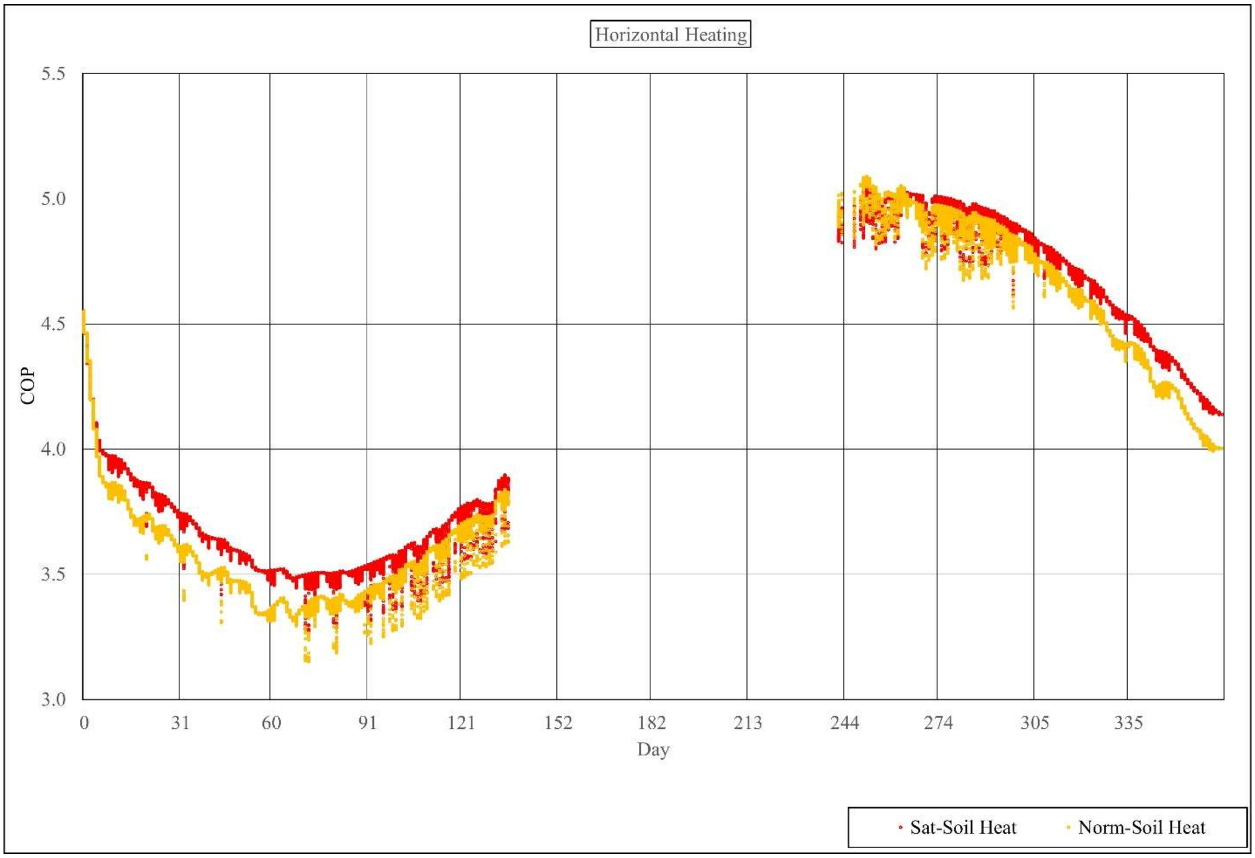


Fig. 4.3 Horizontal heating COP comparison

Similar to the cooling comparison COP, during the heating months, the saturated (modified) COP is better than the normal (unmodified) COP.

With the overall COP of the saturated (modified) soil compared to the normal (unmodified) soil been better, this would lead to less energy consumption for the modified soil. As can be seen below in figure 4.4, the yearly usage of energy of the modified soil is less than that of the unmodified soil.

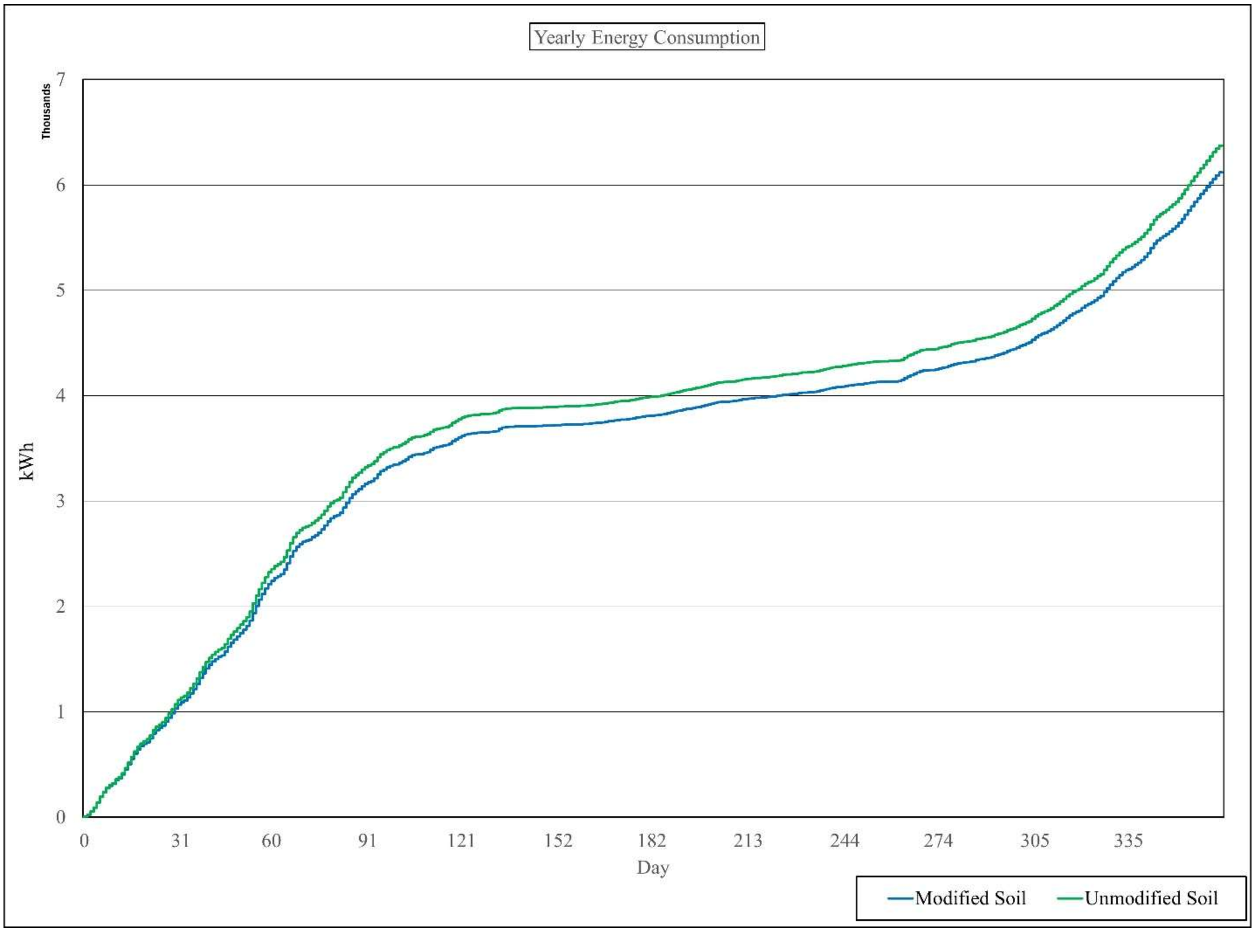


Fig. 4.4 Horizontal energy consumption comparison

Over a period of a year, the unmodified soil used 254.54 kW more energy than that of the modified soil. This is another confirmation that the modified soil is cheaper than the unmodified soil when comparing the two similar horizontal geothermal systems.

4.2 Comparing the new horizontal system to vertical and ASHP systems

As mentioned earlier, the focus on comparison after determining whether the new horizontal system was more efficient, was to compare it to more commonly used systems. This part of the chapter will focus on comparing the new horizontal system to that of a vertical and ASHP systems.

4.2.1 Comparing the temperatures

To begin the comparison of the three systems, the thesis looks at the temperatures each system will run in, shown in figure 4.5. Remember that heat pumps are more efficient than other systems when they are operating in temperatures that are not in the extreme high or low.

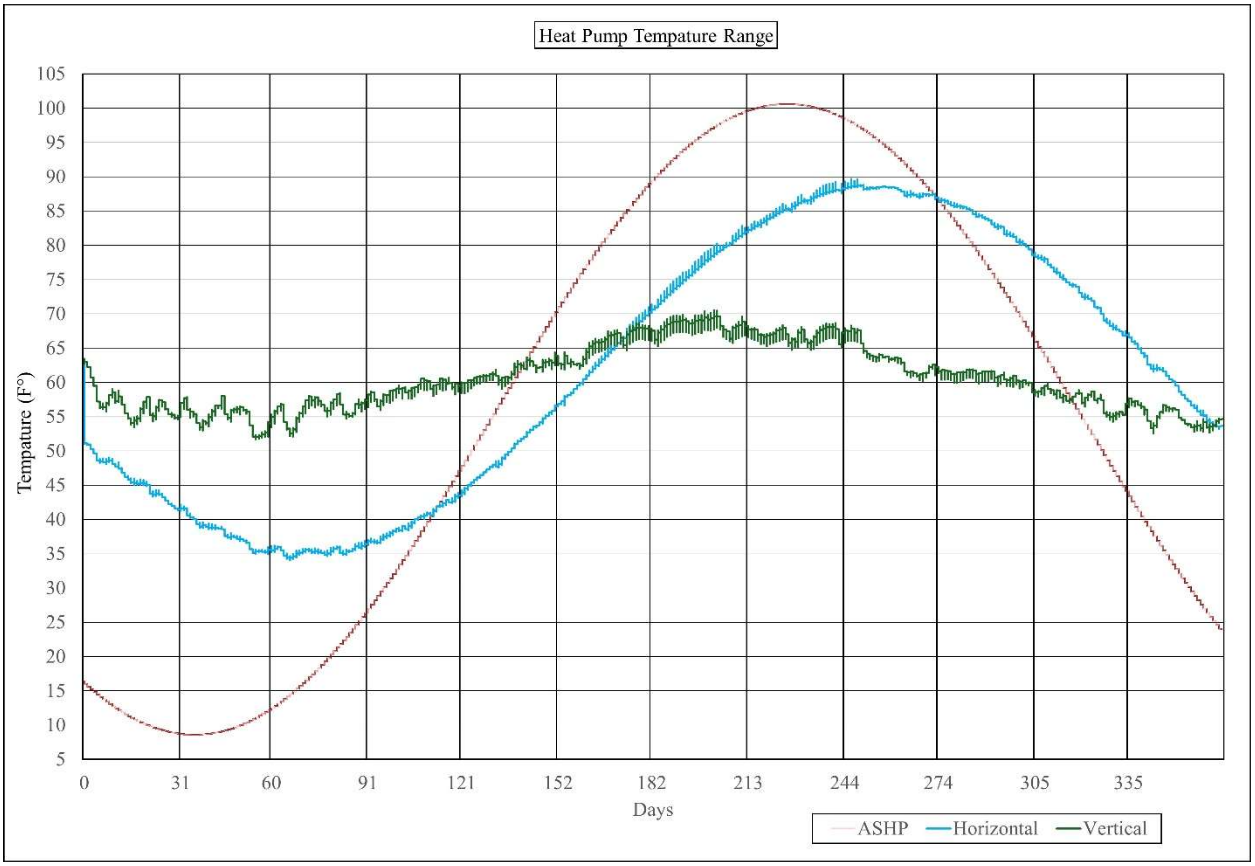


Fig. 4.5 Yearly temperature range of each heat pump

As can be seen from the graph, the geothermal systems operate in a more efficient temperature range than the ASHP, and this shows that an efficiency regression of Vertical-Geo > Horizontal-Geo > ASHP. The vertical-geo temperature is generated by the Dymola program, horizontal-geo temperature is generated by Dymola in conjunction with a sine wave with parameters from [Mesonet.org], and the ASHP temperature was generated by a sine wave and parameters from temperature gathered in Shawnee, OK.

4.2.2 Comparing the COPs

The next step is to compare the COPs of each system, the cooling COP will be looked at first, figure 4.5.

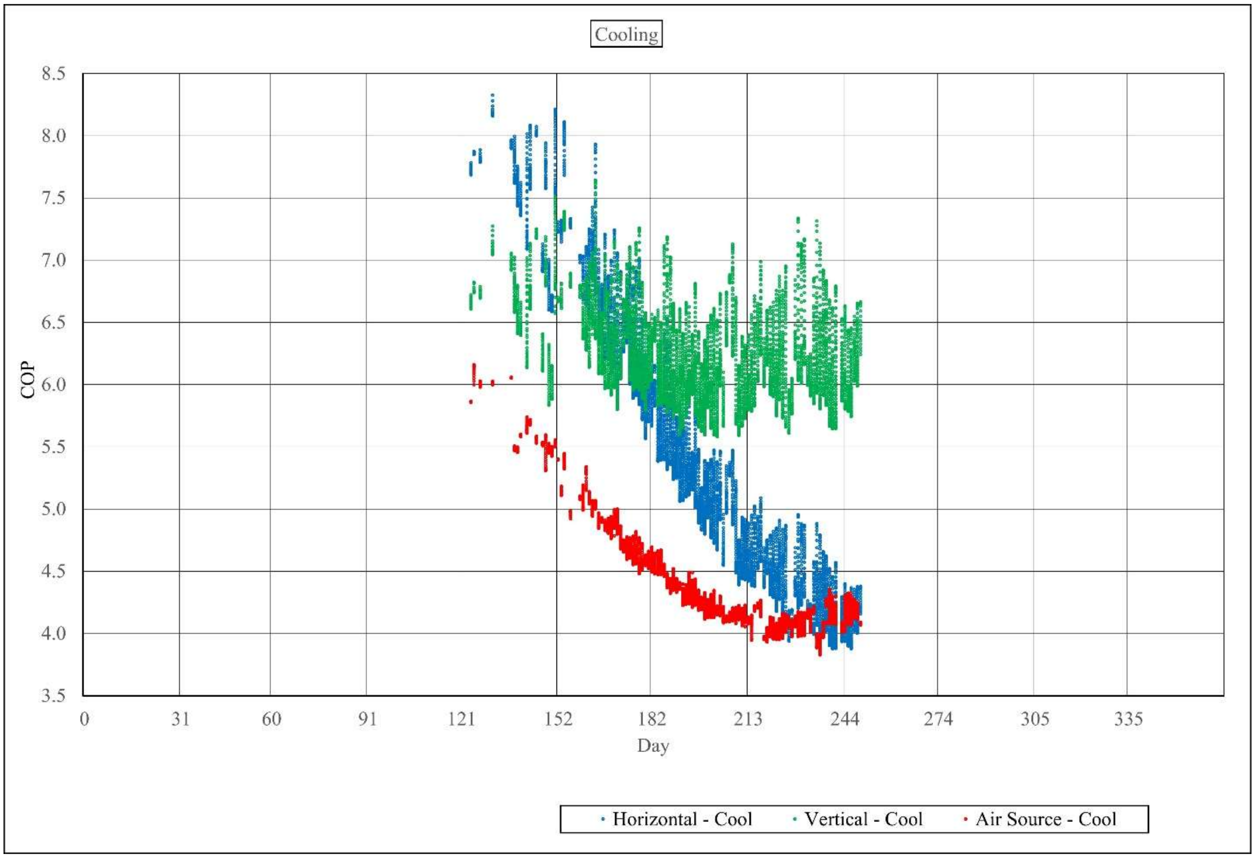


Fig. 4.6 Cooling COPs of the Horizontal, Vertical, and ASHP

For the cooling COP graph, the heating months are shaded, and the cooling months (May to September) are the focus. The cooling was called for during the calendar months by the data gathered to simulate a living unit, which is from an existing occupied home, and if the owner ran the AC during any time it was recorded.

Along with cooling data for the unit, heating was collected and used to develop the heating COP as shown in figure 4.7.

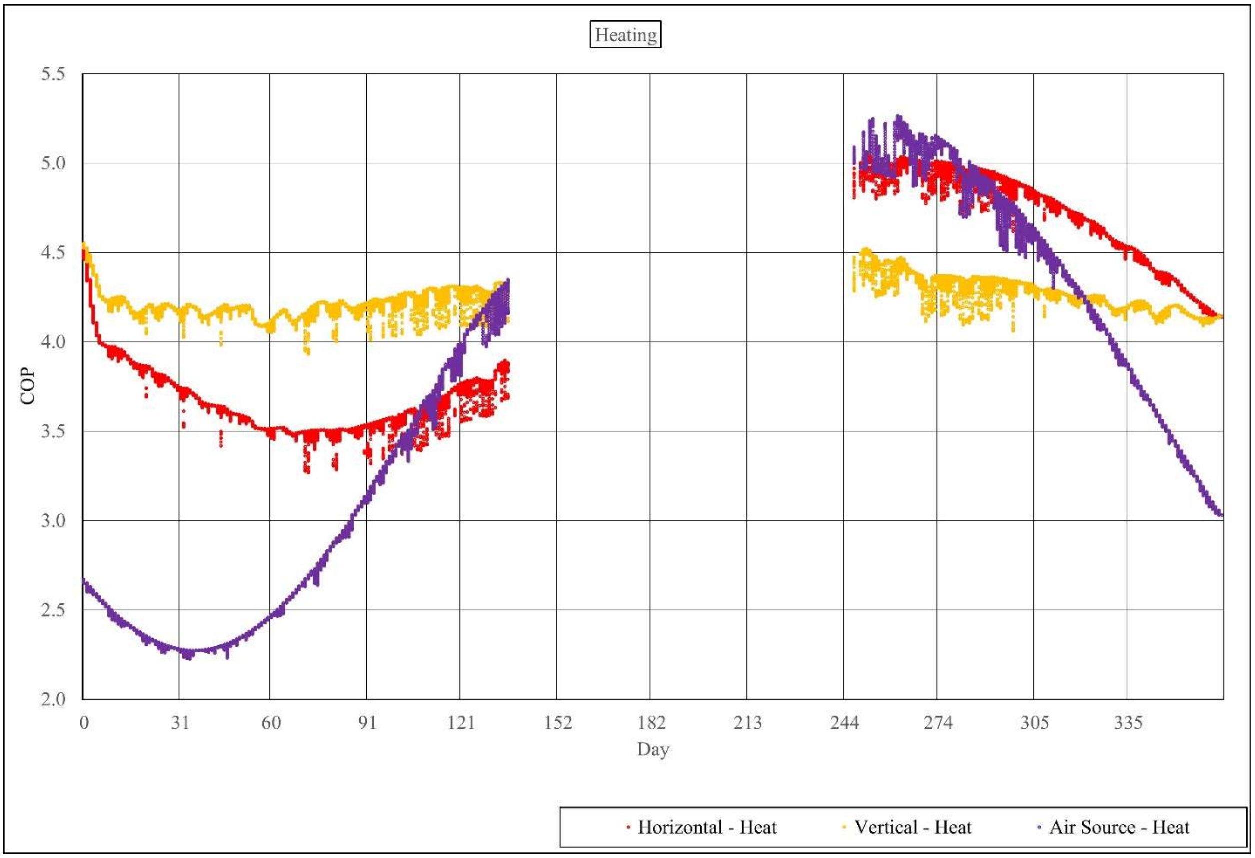


Fig. 4.7 Heating COPs of the Horizontal, Vertical, and ASHP

Just as from the previous COP graph, the heating months (September to May) are the focus. Also, heating was called for during the cooling months is because the data was gathered from an existing occupied home, and if the owner ran the heat during that time it was recorded. One thing to notice, where the graphs overlap, is the season transitioning, indicates switching from heating to cooling & vice versa.

The figures do show the vertical borehole system is more consistent and has a better COP on average. The reason the horizontal system fluctuates more than the vertical system is that the surface temperature of the ground affects the overall soil temperature where the geothermal piping is located. It also indicates that the horizontal system is becoming closer to the efficiency of the vertical system when it is averaged out.

Comparing the COP of horizontal ground source and air source systems as shown proves why geothermal ground source is more efficient than an air source system. The horizontal system doesn't have as low of an average as the air source because of the more consistent and better soil temperatures throughout the calendar year.

4.2.3 Comparing energy consumption

Even after showing the better temperature range and COP increases to the horizontal system, the consumption of power needs to be compared to the other two common systems.

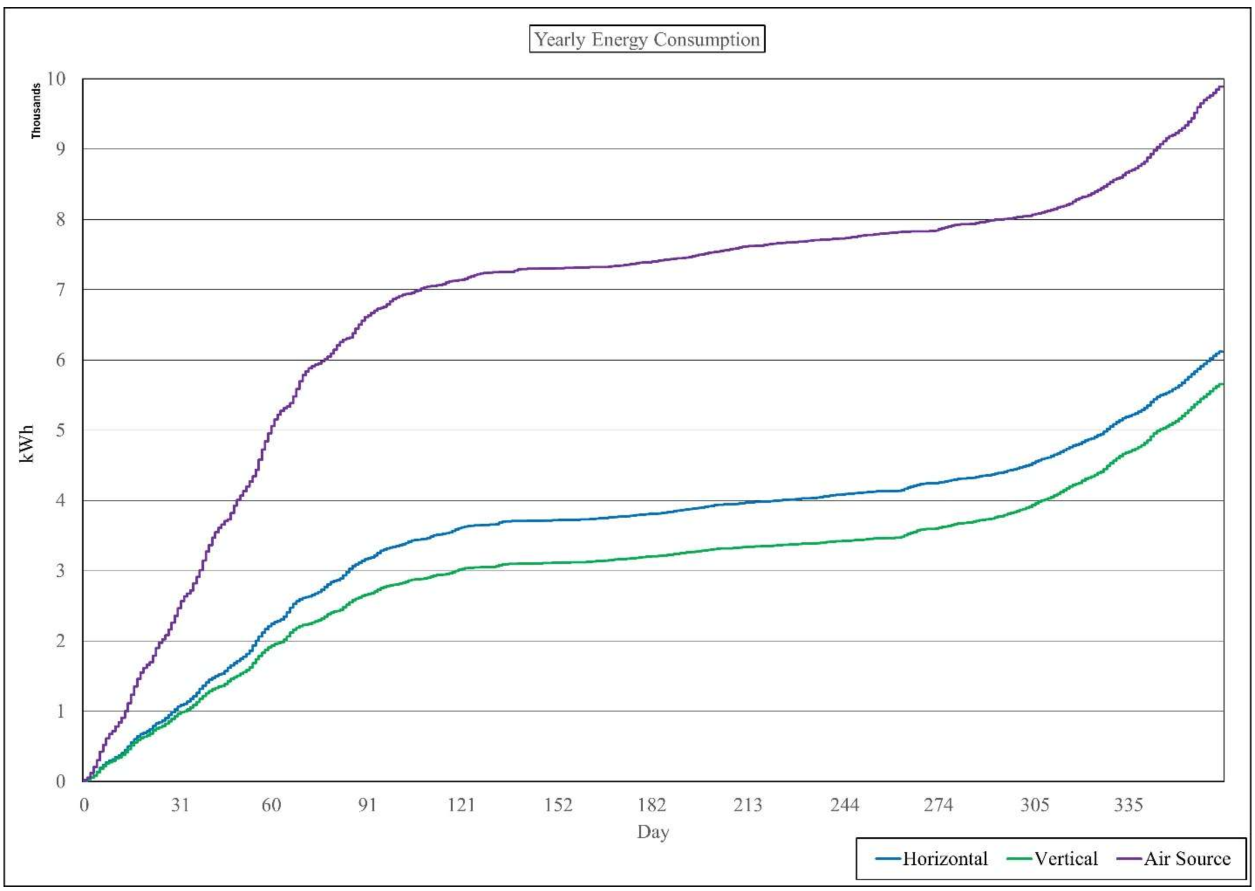


Fig. 4.8 Energy consumption of a year of the three systems

The graph highlights the sharp slope in energy consumption in the cold months, this corresponds to all three systems having lower COPs during the colder months. It also highlights the larger amount of energy needed to run the ASHP system compared to the geothermal ones. Another point to make is that the vertical system is only slightly better than the horizontal system when it comes to total energy used, about 464 kW difference, and the horizontal system used about 3,773 kW less than the ASHP.

Chapter 5: Design of the Combined System

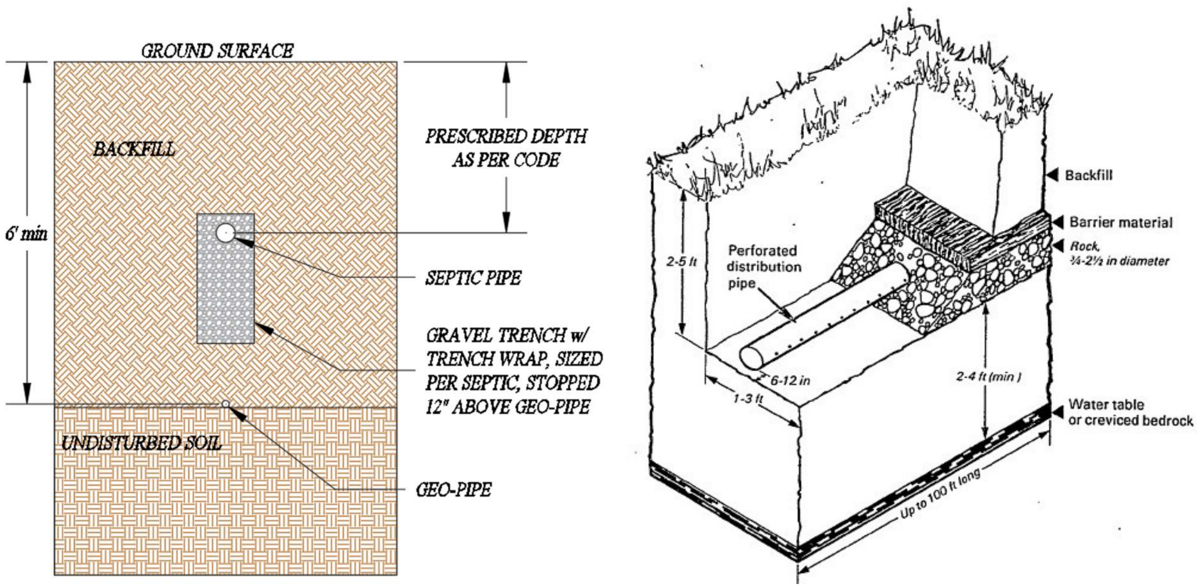
The main objective of the combined system is to deliver wastewater to the geothermal pipes as efficiently as possible to increase the conductivity of the surrounding soil. When simulating this increase in soil conductivity, it was possible for the program to change the properties surrounding the pipe to mimic saturated soil, as illustrated before in chapter 3. There are two main construction types of septic drain fields, one will use trenches and the other excavates the whole field, both can be used in the combined system, see figure 5.1.

(a) (b)

Fig. 5.1 (a) Trench drain field, [septictankcare.net] (b) excavated drain field, [CREDO]

There's more to the drain fields than just trenches or an excavated field. Some can be perforated pipe in a bed of gravel and then covered by the excavated dirt, as in (b) figure, or the perforated pipe on top of a gravel covered by protection shield as in figure (a). It really doesn't matter how the septic system is built; the geothermal system can be laid under it.

In the best design, the septic pipe would be as close to the geothermal pipe as possible, some codes call for a max septic pipe to be three feet, so a delivery system needs to be added, see figure 5.2.



(a) (b)

Fig. 5.2 (a) Design to build the systems together, (b) common septic drain design [inspectapedia.com]

With the septic systems that use gravel trenches, this could be easily adapted to deliver the wastewater to the geothermal pipe, but even the others can still be used. To protect the geothermal pipe, the gravel trench should stop 12" above, this will also allow for maintenance of septic field if needed without disturbing the geothermal pipe. Caution tape should be put on the bottom of the gravel trench as well, warning about the geo-piping below.

A full design drawing of the septic system drain field and geothermal field was intentionally left out for more of an idea of how it should look like, also, septic and geothermal designs very from code and location they're installed in. The idea remains, to deliver wastewater to the location of the geothermal pipe to enhance soil conductivity.

Another method of delivering water to the soil for saturation would be to build the geothermal field under a pond. There are closed loop systems that put the geo-piping into the pond, but over time this pipe gets covered by sediment, and changes its heat exchange rate. It should be designed and built as a horizontal geothermal ground source field with a pond over the top of it, same as the geothermal and septic layered system, see figure 5.3.

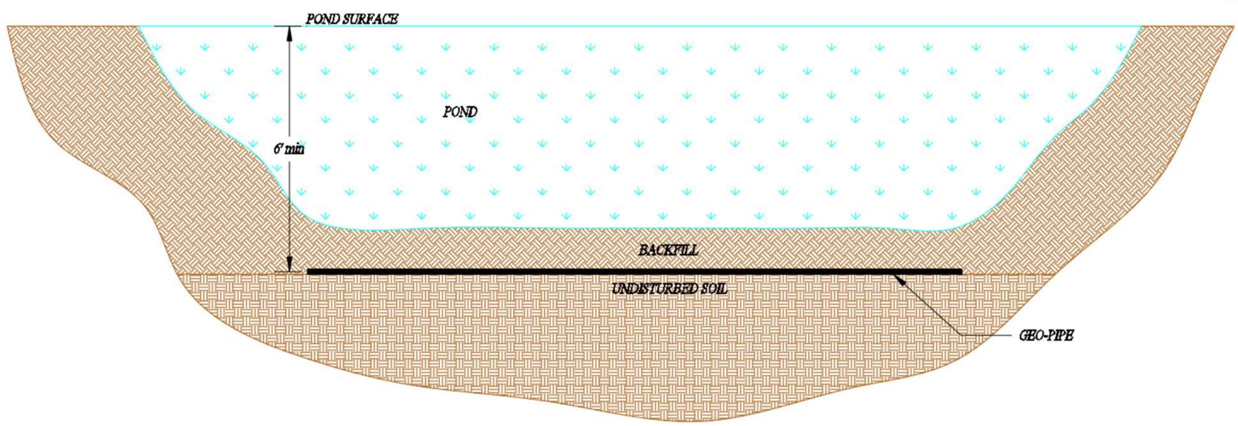


Fig. 5.3 Layered systems of geothermal and pond

Using the pond as a heat sink and source has been designed and built before, but as said before, sediment overtime covers the pipe and changes the bulk conduction of the system. Designing it more into a layered system as in this thesis should develop a better long-lasting system, this wasn't study under this thesis but is another adaptation of the idea.

An additional adaptation using another source of water, using collected rainwater, to feed the geothermal field. Of course, these alternatives are just an adaptation of the idea of using water that would otherwise be sent back into the soil.

Chapter 6: Conclusions and Future Research

This chapter will begin by going over a life cycle cost analysis, which will cover return on investment (ROI) and cost comparison of the other two most common systems. After the life cycle analysis there will be final remarks and future research sections in this chapter.

6.1 Life cycle analysis

When developing the cost analysis of a borehole geothermal system for a project, it was found to be more expensive than previously thought, so an investigation was done on horizontal geothermal fields and in doing so, built onto the idea of this thesis. With combining the septic drain field and horizontal field together, the dirt excavated for the septic field will not be need to be excavated for the geothermal field since it's located above it. What has been found in research, the septic field is larger than the geothermal for the same house it is being installed for, 10,000 sq-ft was chosen based on suggestions from [Sergio et al. 2017], the true size would be determined based on the site's soil properties. For this study, three-foot depth for the septic field and six-foot depth for the geothermal, both measured from the surface. For comparing cost, expenses that would be incurred for all three systems will be left out, only what will be different in each design will be compared.

6.1.1 Comparing cost

Comparing the cost of each system, energy consumption was needed. From chapter 4 details of the total kWh use of each system over one calendar year starting Jan 1st. The data and figure 4.8 highlight the sharp slope in energy consumption in the cold months, this corresponds to all three systems having lower COPs during the colder months. Calculating the cost of energy consumption for the year an average of $ 0.13 per kWh was used, based on Oklahoma average electricity cost. For each system the total cost of the year is $795.49 for horizontal, $735.16 for vertical, and $1,286 for air source.

To further assess the cost of each system, a life cycle analysis needed to be performed. The thesis used a common industry estimator, student version, for the cost comparison [Estimate] full data will be in the appendix. This paper compares the cost with traditional comparable systems, vertical geothermal and ASHP, see table 6.1.

Table 6.1: Cost estimate of all three systems

System	Construction Cost	Energy Cost / Year
Heat pump, water source, horizontal field, geothermal	$ 11,652.47	$ 795.49
Heat pump, water source, vertical borehole, geothermal	$ 23,045.32	$ 735.16
Heat pump, air source, single package (ASHP)	$ 7,236.80	$ 1,286.00

As can be seen, vertical borehole geothermal systems have a high initial cost, and as said earlier this led to the pursuit to develop a more affordable system with near equal operation efficiencies. The two ground source geothermal systems are between 38-42% better energy savings per year compared to the ASHP system, which will help for the return on investment.

6.1.2 Return on investment (ROI)

To help understand analysis of the life cycle cost, a return on investment needed to be investigated. This first analysis does not consider the replacement costs of parts of the systems. Table 6.2 shows the return on investment of the two ground source geothermal systems, only taking into account the savings from energy consumption.

Table 6.2: Return on investment, energy only

Return on Investment	Difference in Cost Vs. ASHP	Energy Cost Savings per Yr. Vs. ASHP	Time Period (Yrs.)
Heat pump, water source, horizontal field, geothermal	$ 4,415.67	$ 490.51	9.00
Heat pump, water source, vertical borehole, geothermal	$ 15,808.52	$ 550.84	28.70

The table shows that it would take 9 years for the horizontal system and about 29 years for the vertical system to even out the cost compared to the ASHP system. This shows that the horizontal return on investment is nearly 1/3 of the time compared to the vertical system, and this is only taking into account the energy cost.

Typically, outdoor condenser units, which the ASHP system uses, are replaced every 10 to 15 years. The geothermal ground loops can last up to 50 years, some believe they can reach 100 years. So, the return on investment time period would be even shorter, taking into account the replacement of the outside units of the three systems, table 6.3 takes into account replacing the ASHP outside unit.

Table 6.3: Return on investment, replacement added

Return on Investment	Difference in Cost Vs. ASHP	ASHP Condenser Replacement Cost	Energy Cost Savings per Yr. Vs. ASHP	Time Period (Yrs.)
Heat pump, water source, horizontal field, geothermal	$ 4,415.67	$ 2,416.16 x 1	$ 490.51	4.08
Heat pump, water source, vertical borehole, geothermal	$ 15,808.52	$ 2,416.16 x 2	$ 550.84	19.93

When taking into account the replacement cost of the outside condensing unit for the ASHP. Comparing the ASHP to the horizontal system, if the condenser had to be replaced earlier than the average timeframe, the return on investment would be around 4 years by replacing the condenser 4.08 years or less. Now comparing the ASHP to the vertical system, it would most likely need the condenser replaced twice within the ROI energy cost. So, with two replacement costs for the outside unit, the ROI for the vertical system is about 20 years. This illustrates that the horizontal ground source geothermal system has a better ROI, compared to the vertical system, between 4 and 9 years.

6.2 Final Remarks

This paper shows that increasing the conductivity of soil will increase the energy transfer rate, which will increase the efficiency of a system using the soil as ground source "battery". This system will work well for new construction of a house that requires a septic system, and it can also be adapted to an existing home when the septic drain field / system is being replaced. The combined system gives consumers more options when considering a more efficient HVAC system. With the simple design of combining the two systems, septic drain field, and horizontal geothermal field, the required construction takes less specialized equipment and skill to build, lending a hand to individuals that would like to adopt it. Combining the required construction jobs will bring down the overall cost of the project. A more in-depth review of the life cost analysis will show an even better return on investment for this system.

6.3 Future Research

For further research on this idea, a more comprehensive simulation should be developed. The simulation software has specific programs built inside of it to perform a simple test of the hypothesis. To get a more in-depth analysis, reprogramming those built-ins with more control over changing parameters would allow for further research into the effects of differentiating soil properties and surface temperature with respect to outdoor air temperatures, instead of developed sine waves. This would give a much better comparison to ASHP and vertical geothermal systems.

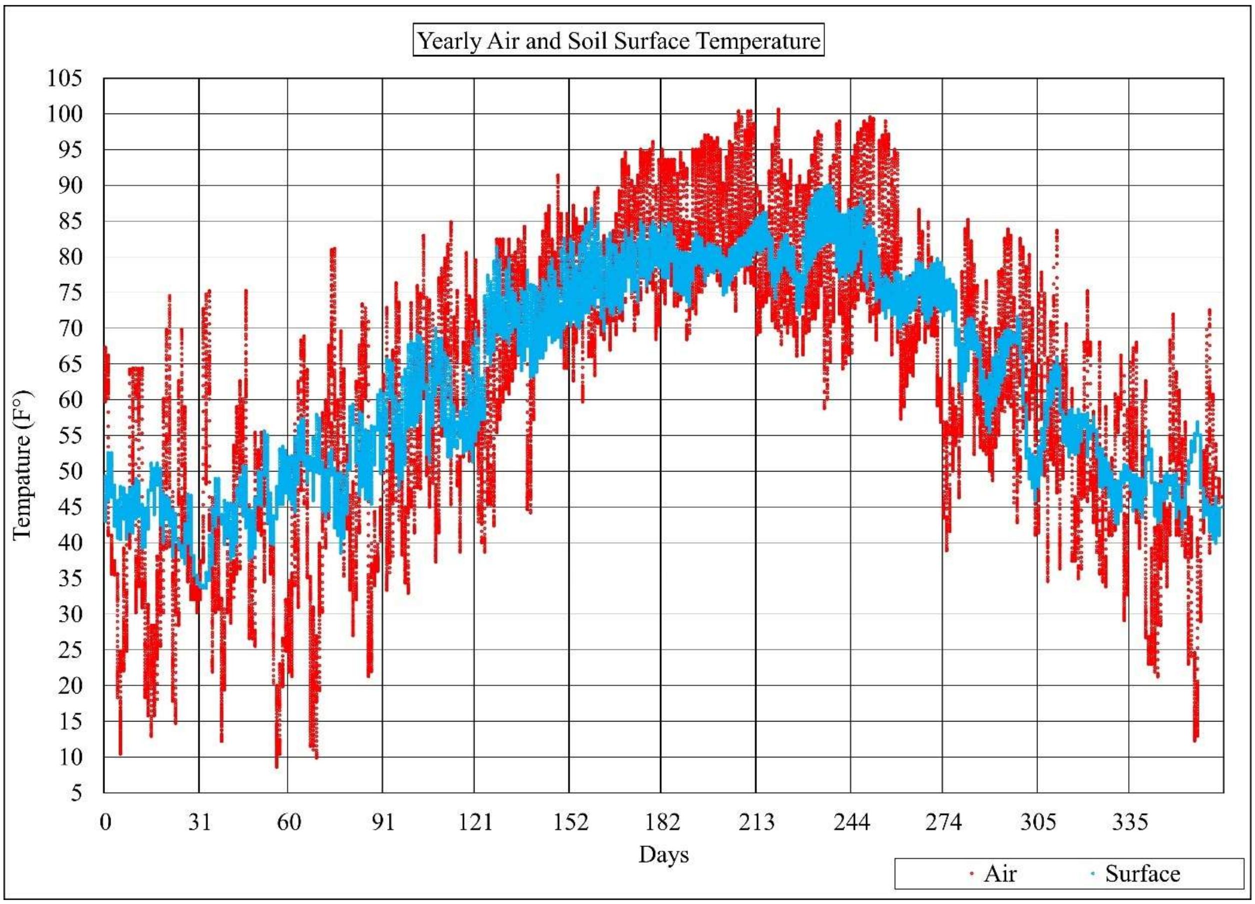


Fig. 6.1 Real-world temperatures of Shawnee, OK

Figure 6.1 shows temperature data from Mesonet.org for a full calendar year. Using this data for the horizontal geothermal and ASHP systems would give more accurate analysis of them.

There could be further analysis from other water sources, building the system under a considered pond, or using other sources of water, as in collected rainwater.

Development of operational controls of the combined system would be new to the industry. A study would need to be conducted on predicting how to operate the system based on the use of water from the household or measured soil saturation. As in, if the wastewater out-put drops it could indicate a smaller occupancy in the household, which would tell the system there should be less load for HVAC.

6.4 Real world application

There is planning for a fully built operational system for a newly built 1700+ sq-ft home. This would allow for data acquisition and operational analysis of an actual built system being used in the real world.

6.5 ASHRAE paper

A paper has been written over this thesis for ASHRAE, it was accepted and will be presented at the AHSRAE summer conference this June, 2025.

REFERENCES

BuildingAdvisor.com, https://buildingadvisor.com/buying-land/septic-systems/how-a-septic-system-works/.

Buildwithrise.com, https://www.buildwithrise.com/stories/costs-and-benefits-of-ground-source-heat-pumps.

Capitalheat.com, https://capitalheat.com/solutions/geothermal-101/.

CREDO construction, INC., https://www.credoconstruction.com/portfolio-item/kobes-residence/.

D.H. Welte, B. Horsfield, D.R. Baker; 1997, Petroleum and Bason Evolution.

Ellen Hunter, 2023, https://www.learnancientrome.com/how-to-ancient-romans-stay-cool/.

Estimate – RSMeans, Student Version, MasterFormat 2018, Year 2024 Quarter 1.

Gehlin, S., 2002, Thermal response test: method development and evaluation.

Giorgia Dalla Santa, et al., 2020 An updated ground thermal properties database for GSHP applications

HVAC School, https://hvacrschool.com/how-a-heat-pump-reversing-valve-works-2/

IGSHPA, 2017, Closed-Loop / Geothermal Heat Pump Systems Design and Installation Standards.

Lev, Izzy, Arkad; 2014, Applied Geothermics.

Mesonet.org, https://www.mesonet.org/weather/soil-temperature/soil-temperature-graph?ref=1253&stid=shaw.

Microsoft Copilot

Modelica Buildings library, https://simulationresearch.lbl.gov/modelica/downloads/archive/modelica-buildings.html#

R. Hurt, K.A. Ejenakevwe, J.D. Beaty, G. Wang, J. Cai, Z. O'Neill, L. Song, 2025, A Simulation Study of Single Pipe Geothermal District Heating and Cooling Network Pumping Control Strategies and Performance (In Review).

R. Hurt, K.A. Ejenakevwe, L. Song, X. Wu, 2025, Estimation of the Average Soil Thermal Conductivity and Grout Thermal Resistance from the Thermal Response Test using Nonlinear Regression.

septicshoppe.com, https://septicshoppe.com/septic-101/.

septictankcare.net, https://septictankcare.net/what-are-drain-fields-made-of/.

Sergio M. Abit Jr., Emily Hollarn, October 2017, Basic Septic System Rules for Oklahoma, Oklahoma Cooperative Extension Service PSS-2918.

U.S. Energy Information Administration (EIA), https://www.eia.gov/