Analysis of Heat Transfer in a Geothermal Cooling System

Meeg342 Honors Research Project

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1 Introduction

Before we can optimize a geothermal system we must first understand all the components and how each part interacts with the rest of its system. This paper will first give a brief overview of the different components, the different type of underground loop systems on the market, and then finally address the heat transfer problem with the underground loop systems and see what areas can be optimized.

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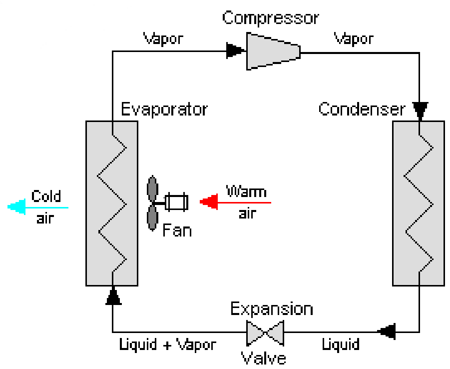
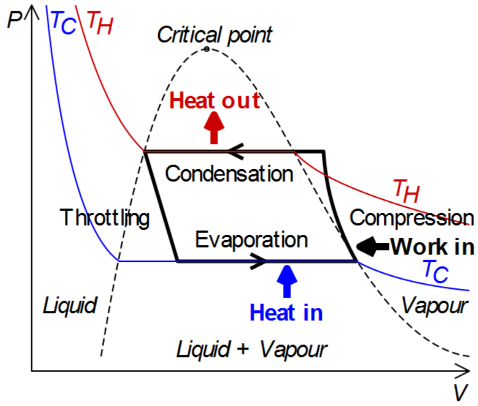
2 Standard Heat Pump System

A normal heat pump cooling system fitted on most houses uses the vapor compression cycle to allow for cooling. This cycle allows for the removal of heat from one source and the exchange of that heat into a secondary environment. During the summer a house cooling system is removing heat from the inside and dumping it outside. The opposite is true for a house heating system. When looking at the components of the vapor compression cycle there are four basic parts: a condenser, evaporator, compressor, and expansion valve.



(a) Example vapor compression cycle with components. *Wikimedia Commons [1]*



(b) Pressure verses specific volume of working fluid inside compression loop. *Wikimedia Commons [2]*

By following the refrigerant liquid around the loop we can look at the impact of each part. First the pressure is increased by the compressor doing work on the fluid. This increases the internal temperature of the working fluid and converts it into pressured gas. Then the fluid is put through a condenser which removes this heat and condenses the gas back down to a saturated liquid. After going through an expansion valve to drop the pressure and thus lowering the over all temperature the fluid can go through another heat exchanger called a evaporator which removes heat from and environment. This cycle can be repeated as long as work, in most cases electricity, is applied to the compressor. During summertime operations the cool evaporator is run indoors and the heat from the indoors is “dumped” into hotter outside. During the winter heat is extracted from the outside and then dumped into the indoors through a condenser.

3 Geothermal Heat Pump System

Geothermal heating systems look to replace one of the components in the standard vapor compression cycle. In this case geothermal replaces the standard condenser with its own. Most heat pump systems have their condenser sitting on the outside of the house where the coolant is run through finned coils and a fan blows air over it to exchange the heat with the outside air. Geothermal on the other hand looks to replace this with a underground system of loops. Intuitively one would think that the earth does will not be affected as much to the weather, seasons, and air temperature on the surface, and one would be right. It is shown that the ground below the frost layer is on average a constant 13-22 degrees celsius year around [3]. The thought process is that there is a energy "sink" in the ground that provides a constant temperature no matter what the outside temperature is.

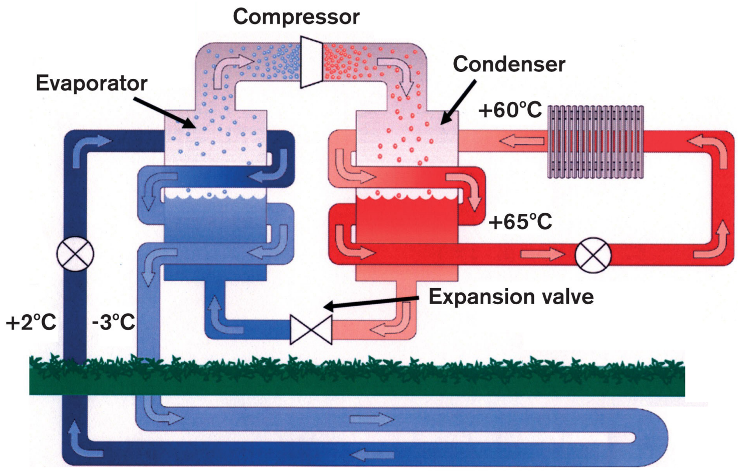


Figure 3: Implementation of geothermal heat pump in a winter configuration. *Bay Star Energy [4]*

As seen above, for a winter cycle, the ground is used to heat a working fluid that goes through a loop in the ground. This fluid then goes through a heat exchanger to give the heat into the normal heat pump cycle. The heat pump cycle remains unchanged besides from this replacement of the outdoor physical heat pump with a underground loop system.

4 Heat Exchange Through Ground Loop

To isolate the ground loop for further studying we will first look at what type energy is needed and expected from the ground loop to dissipate. In this case we will consider a average four bedroom home heat lost. This would normally be calculated using the Manual J. form provided by the ACCA [5], but here we will focus on a hypothetical scenario. It is important for contractors to properly calculate the heat lost estimates. The Manual J. provides the designer with a room by room energy lost and a whole house energy lost. Using this information any heating or cooling system can be properly sized. Since we are focusing on a hypothetical case, we can create constraints that will allow us to look at specific individual parts of the system

We will consider the geo-thermal heat pump ground loop. This is the main component that has a large about of variations based on the different environments and soil conditions offered. All cooling loops aim to cool down the working fluid by transferring heat to the outside medium. The most common is to bury the cooling loops in the ground, but another option is to put the loops in a larger body of water such as a pond or lake. Withing the soil type cooling loops there are different types of configurations. To explain these visually, please examine the figures below.

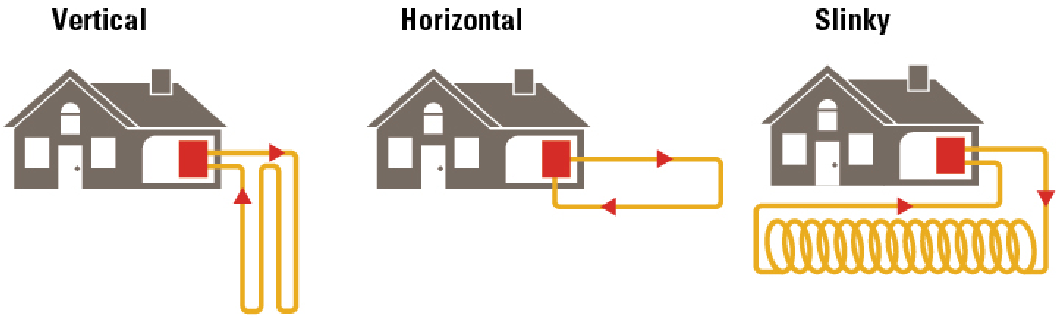


Figure 4: Different closed loop geothermal cooling loops. *Mississippi Power [6]*

One of the common types of configurations is the vertical well. Vertical holes are drilled several meters into the ground and a u-shaped pipe is put vertically into the column. This vertical method is popular because the yard of the customer's house does not need to be torn up, and because it reaches deeper into the constant temperature soil it is less effected by the above ground weather. With each of these types they come in two configurations series and parallel. Parallel is preferred in most installations because it allows for smaller pump to drive the entire system. In the next section we will formulate the problem and look at the heat transfer between the ground loop and the outside soil.

5 Ground Loop Problem Formulation

The problem is formulated as the following. To motivate the problem we are looking to calculate the outlet temperature, and pressure drop through a pipe system if we know the flowrate and inlet temperature. For geothermal heat pumps most systems circulate a mixture of water and antifreeze coolant. For our formulation we will assume that the antifreeze has a small effect and can be ignored in the calculation. To find the outlet temperature we must model the heat transfer properties. A thermal resistance circuit can be created like the following.

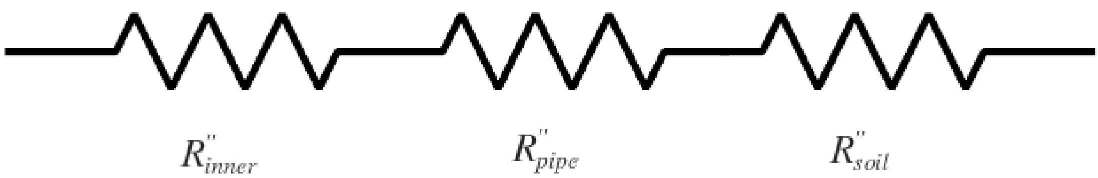


Figure 5: Thermal resistor system, moving from the inside fluid convection, conduction through the pipe wall, and conduction to the outside soil.

First we are interested to calculating the internal convection due to the water and the inner pipe surface. First we calculate the Reynolds number for the flow using our estimated volumetric flowrate, inner diameter and cross section of the pipe.

$$Re_D = \frac{QD_h}{\nu A_c} \tag{1}$$

Once the Reynolds number is known we can select the correct formulas to calculate the convection coefficient for the pipe. To do this we must first calculate the Nusselt number and combine this with the definition of the average convection coefficient.

$$Nu_D = \frac{(f/8)\,(Re_D - 1000)\,Pr}{1 + 12.7(f/8)^{1/2}\left(Pr^{2/3} - 1\right)} \tag{2}$$

$$Nu_D = \frac{hD_h}{k} \rightarrow h = \frac{Nu_D k_{water}}{D_h} \tag{3}$$

To find the Nusselt number the Gnielinski correlation can be used for flows that has $Re_D > 3000$. The benefit of using this correlation is that it takes into account the roughness of the pipe wall with the Darcy friction factor f. The Darcy friction factor can be found using the moody diagram or by using the use of the Colebrook-White equation.

$$f = \frac{64}{Re} \; for \; Re < 2000 \tag{4}$$

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}}\right) \; for \; Re \geq 2000 \tag{5}$$

When the flow is not laminar a constant can be used to approximate what the Nusselt number. Using Table 8.1 from [7] the Nusselt number is $Nu_D = 3.66$. Using this friction factor and Nusselt number equation we can finally find the convection coefficient of the inside pipe. Next the thermal resistance for the pipe wall can be calculated. Using the CES material selector [8] the following material properties where found for the three common types of pipes used for installation.

Type	Thermal Conductivity (W/mk)	Density (kg/m^3)
HDPE Pipe	0.461-0.502	947-955
PVC Pipe	0.147-0.209	1300-1490
CPVC Pipe	0.133-0.144	1450-1560

Using these conduction values the heat transfer through the pipe can be calculated. Furthermore the heat transfer into the soil can also be calculated in a similar way. We look to find the conduction coefficient of the soil that that geothermal heat pump pipes will be buried in. This will vary from region to region but also it is a function of multiple variables. As seen in the work done by Farouki [9] the thermal properties vary largely as a function of Quartz content, crushed or natural, coarse or fine, dry density, and degree of saturation.

$$R_{total} = R_{inner} + R_{pipe} + R_{soil} = \frac{1}{hA_s} + \frac{ln(r_o/r_i)}{2\pi Lk_{pipe}} + \frac{ln(r_\infty/r_o)}{2\pi Lk_{soil}} \tag{6}$$

We will assume that the user knows this value has has calculated it using the equations noted in [9]. From this the total resistance can be calculated for the entire system. Now that we know how to calculate the total resistance we can find the outlet temperature by using the log mean temperature difference energy balance. This balances the mass flowrate with the overall change in temperature through the system.

$$\frac{(T_\infty - T_{m,o})}{(T_\infty - T_{m,i})} = exp\left[-\frac{1}{\dot{m}C_pR_{tot}}\right] \tag{7}$$

We know what our T_∞, $T_{m,i}$, pipe type, length, and how to find the total resistance for the material. With these we can calculate the outlet temperature and the total energy transferred into the ground. Both of these values can be used to correctly size a pipe system.

6 Ground Loop Computational Results

We can construct a MATLAB program that allows use to simulate different possible scenarios. In doing so we hope to discover key conditions that would make a ground loop system favorable for the buyer. The implementation has ignored the resistance added by the soil. In practice if the designer can calculate how far radially outward the temperature gradient in the soil becomes close to zero the derived formulas can be used. The soil is a infinite medium and thus would have to be solved with a unsteady diffusion formulation. The problem is formulated with a 1" HDPE pipe with a wall thickness of 1/16". The mass flowrate is varied to see how this affects the outlet temperature. The inlet temperature is around 73 degrees and the ground was taken to be 55 degrees which is the average ground temperature in Delaware [10]. Using these assumptions the pipe system can be simulated.

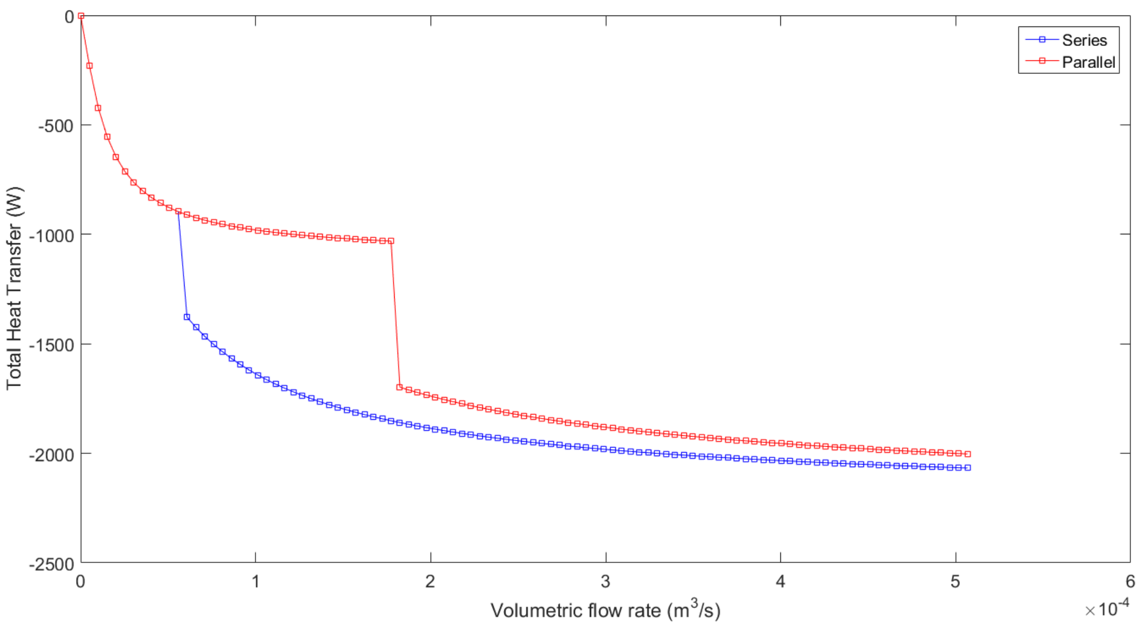


Figure 6: Total heat transfer for a 30 meter long pipe with varying flowrate. Parallel uses 3 tubes being of length of 10 meters.

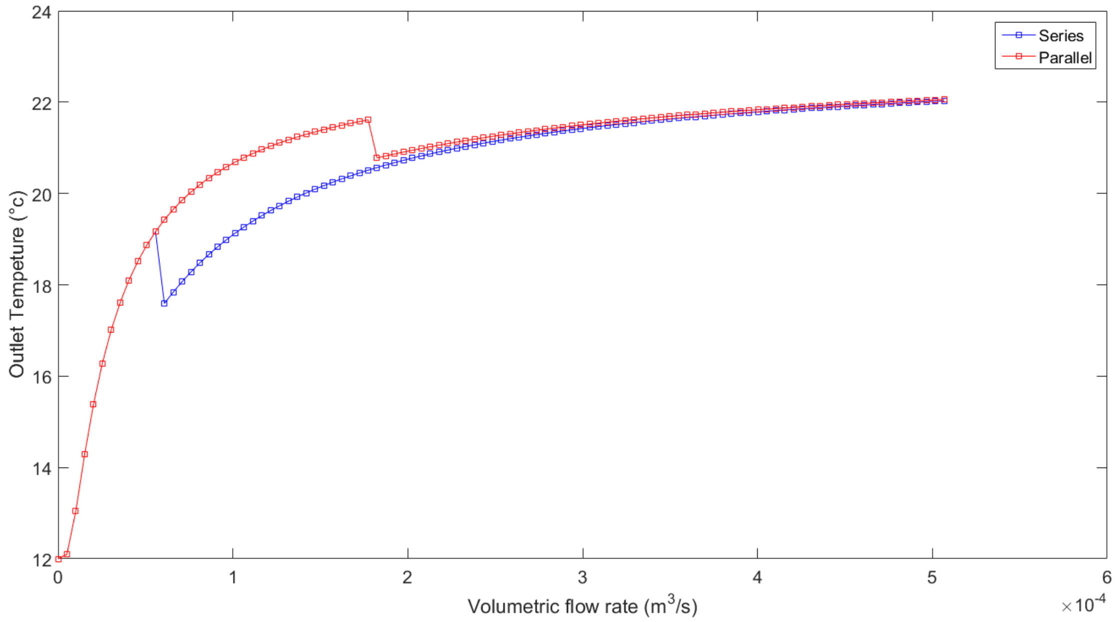


Figure 7: Final outlet temperature for a 30 meter long pipe with varying flowrate. Parallel uses 3 tubes being of length of 10 meters. Note the jumps are from the transition from laminar to turbulence.

As seen above there are some very interesting results. The goal of the water loop system is to cool down the hot water exiting the house. This temperature difference can be used in a heat exchanger attached to the house's vapor compression HVAC system to provide summertime cooling. When selecting a system it can be seen that when a series system the flow transitions to turbulent at a lower *total* mass flowrate and therefor allows for a higher heat extraction compared to the parallel configuration.

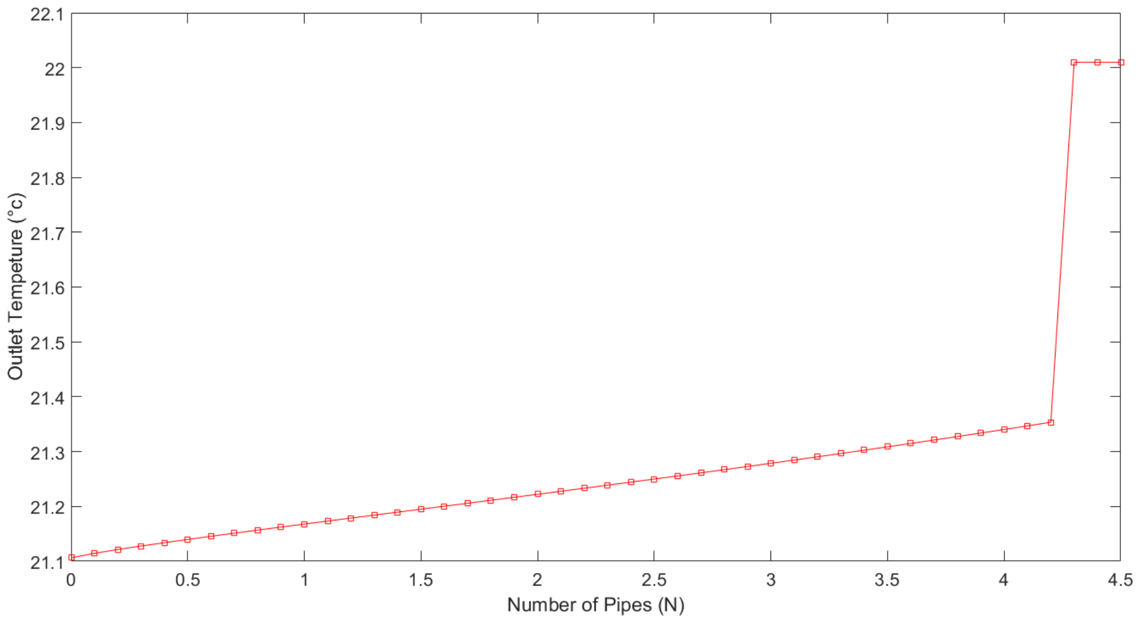


Figure 8: Final outlet temperature for a varying number of 30 meter long pipes.

Additionally as seen above as more pipes are added to a parallel system the outlet temperature converges back to the inlet temperature. This is likely because while the total mass flowrate stays constant the flow through each individual pipe decreases and causes a drop in the convection coefficient. The jump seen above shows the transition to laminar flow in all the parallel pipes. A series system has better thermal performance over a parallel system. The downfall to using a series system is that it is likely that a large pump will be needed to reach the same equivalent flowrate of a parallel system.

In conclusion, a series system allows for higher thermal performance when compared to a parallel system. The parallel system allows for a smaller circulation pump to be used, but has poor heat transfer due to the lower flowrates through the individual pipes in the system. When sizing a system, the total energy needed to be exchanged through the heat exchanger can help select a proper length of tubing.

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