Computational Analysis for Differing Design Variables of a Closed-Loop Geothermal Heating and Cooling System

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1 ABSTRACT

The purpose of this report is to investigate the effects of various parameters in a horizontal loop geothermal heat pump system. The obtained values include the temperature distribution over the entire system as well as the exiting temperature and bulk heat rate of the fluid. The results calculated in this report are set over a 6 month heating period.

2 INTRODUCTION

This project will be looking at specific parameters and their effects on the underground portion of a geothermal system. Before the project is explained there is a need to explain both, what geothermal is and what methods are going to be used to simulate the geothermal system.

2.1 Geothermal Heating and Cooling

2.1.1 Brief History

Geothermal heating and cooling is not the product of the recent green movement that many people are familiar with. In fact, geothermal heating and cooling has been around for many years. One of the earliest records of a ground source heat pump dates back to the mid 1940's. R. C. Webber was one of the first to build a ground source heat pump that could produce 2.2kW of energy. His method was to evaporate CFC refrigerant in underground copper pipes (1). Since these initial designs, geothermal heating and cooling has become a much more efficient way to heat and cool compared to traditional methods.

2.1.2 How it Works

Most modern geothermal heating and cooling systems operate on the same basic idea. They use the constant temperature of the ground to either put energy into, or tame energy out of a fluid. Normally this fluid is water.

There are 2 different ways commonly used to get this water. The first is using a closed loop system. This is the more common and traditional method for geothermal systems. The basic idea is to run a fluid through a series of underground pipes. As the fluid flows through these pipes it either gains or losses energy based on whether it is in cooling or heating mode. This will be explained further in a later section. This type of system offers a lot of versatility when it comes to setting up the piping. Figure 1 below illustrates 3 common types of closed loop instillations.

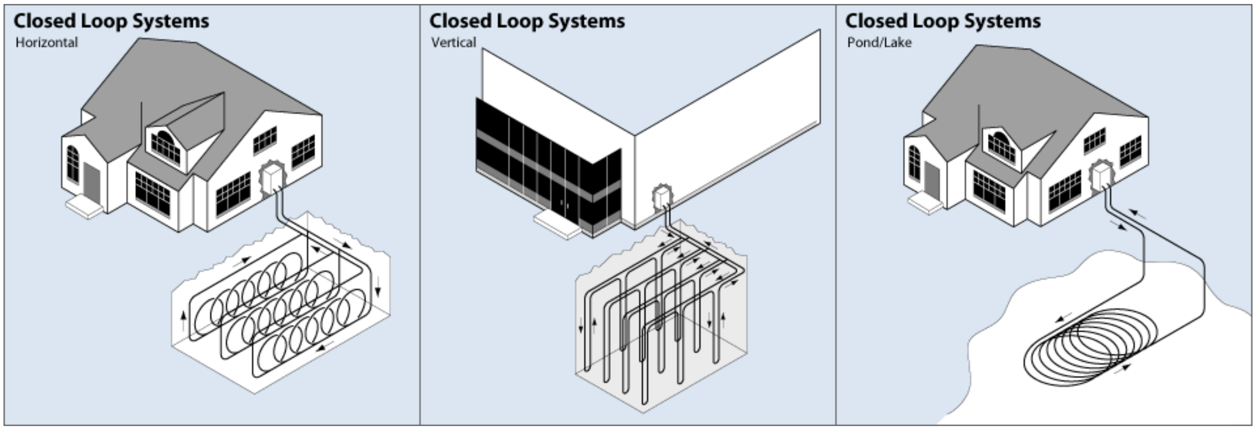


Figure 1. Three Types of Closed Loop Systems (2)

Each one of these systems illustrated in Figure 1 have very noticeable visual differences, but what may not be so obvious are the differences in instillation cost. For instance, the first system illustrated has a horizontal pipe layout. With this layout, it is only necessary to dig a trench for the pipes from 4 - 6 feet deep. This can cut back on the instillation cost, but uses up a larger amount of area. This makes it ideal for residential areas where horizontal space is not an issue. The second system that is illustrated is the vertical loop system. This system requires sections of the pipes to be placed into holes that can be anywhere from 400 - 600 ft deep. This can lead to a higher instillation cost compared to the horizontal system. However, the vertical system takes up much less surface area. This makes it ideal for places where there is not a lot of open area available to put in this instillation. The last type illustrated is the pond/lake system. This system is the easiest and cheapest to install. However, it is the one that also needs the most specific conditions to work in. The first limitation is that it needs a pond or lake to work. The basic idea behind this system is to use the water that can be found at a constant temperature instead of the earth. This means it requires no digging that drops a lot of instillation costs. However, not just any pond or lake can work. For instance, the Department of Energy suggests that a system like this be installed in a body of water no less than 8 ft deep. This is to prevent freezing. On top of this there are also volume and quality criteria that must also be met. (2).

The second method that is commonly used in geothermal heat pumps is an open loop system. In this system the water is not moved through the pipes but rather, well water is taken from the ground, used in the system and then returned. Since this water is already at the temperature of the earth, there is no need to run it through a series of pipes. Figure 2 below illustrates this basic idea.

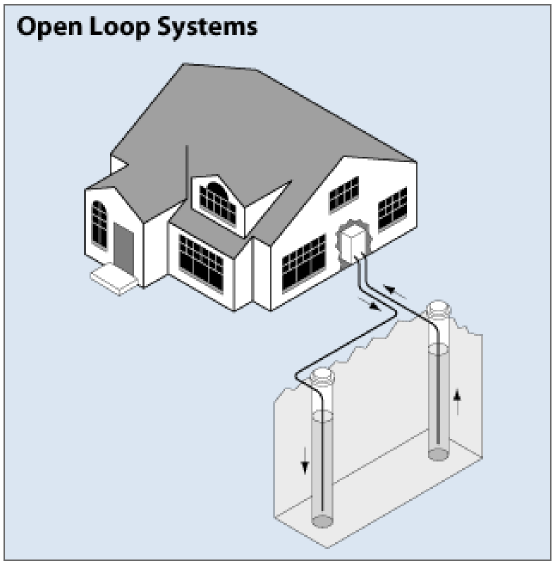


Figure 2. Open Loop System

The open loop system can be much more cost efficient when it comes to instillation. Instead of a need for digging up a large area for the instillation of pipes, there just need to be a few holes drilled down to the water level. However, like the pond/lake loop system, this system can only be used in certain areas. Not all areas have a sufficient underground water supply. Another problem that can arise is the water may be too high in impurities and minerals that can cause damage to the system (2). However, there are ways to combat this problem.

2.1.3 Geothermal Heat Pumps

Although not the focus of this project, the geothermal heat pump is the most important element in a geothermal heating and cooling system. The heat pump itself is what supplies the area with warm and cool air. Geothermal heat pumps work on a basic compression and expansion cycle. When heating is desired, the water is introduced to the system at the evaporator phase shown in Figure 3. For a liquid to air heat pump, air is then blown over the condenser and carried to the desired location. For cooling, the process is reversed; water from the ground loop is introduced at the condenser side to draw energy out of the system. Air is then blown over the evaporator side, cooled and carried to the desired location. (3)

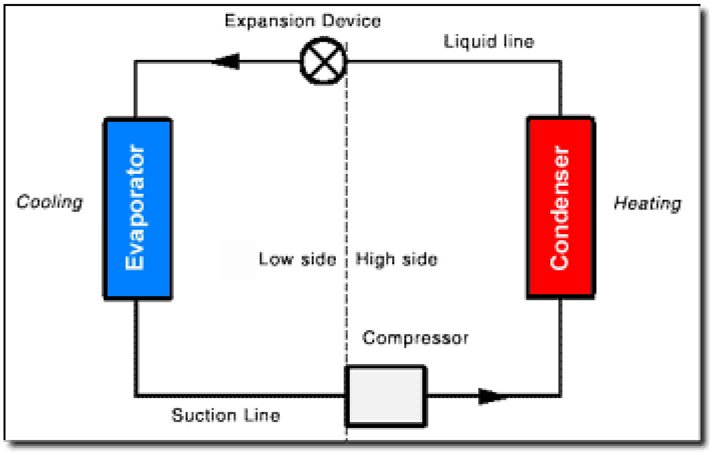


Figure 3. Heat Pump Block Diagram.

2.2 Computational Method Used

2.2.1 Basics

The program used in this project was developed by Dr. James Menart. Its basic function is to solve an unsteady, two dimensional heat transfer problem, taking into account the effects of conduction and convection. This program was specialized however, to focus on the effects of a closed loop geothermal system. It is capable of finding the temperature distribution through the all entities in the system; this includes the liquid in the pipes, the pipe itself and the ground surrounding the pipe. The program is also capable of calculating the exit temperature and energy gain of the fluid traveling through the pipe. All these results are displayed for different parameter values in this report.

2.2.2 Fundamental Equation

All values in this program are found using the following fundamental equation.

$$\frac{d\left(\rho C_p T\right)}{dt} + \frac{d\left(\rho C_p u T\right)}{dx} + \frac{1}{r}\frac{d\left(r \rho C_p v T\right)}{dr} = \frac{d}{dx}\left(k\frac{dT}{dx}\right) + \frac{1}{r}\frac{d}{dr}\left(kr\frac{dT}{dr}\right) + S$$

Where:

ρ	Density of material
C_p	Specific heat of material
u	Fluid velocity
r	Radius
v	Volume

k	Thermal conductivity
T	Temperature

This equation is used in a repeating process. The equation is first used with known boundary conditions at a certain time step. These values are used to approximate the values for the surrounding system. This process is repeated until the values stop changing within a certain bound. The program then moves to the next time step and repeats this process.

2.2.3 **Fluid Flow Properties**

For the version of the program that was used in this report, the effects of turbulent flow were ignored. The flow was approximated to have a parabolic profile through the entire length of the pipe. The program has since then been updated to take into account the effects of turbulent flow.

2.2.4 **Design Mesh Used**

An expanding mesh was used in this program to control the degree of precision in the 3 separate materials. The mesh only expands in the radial direction and remains constant in the axial direction. There are separate settings that can be used for the mesh in each material (earth, pipe and fluid).

2.2.5 **Alternative Methods**

The program used in this project just presents one possible method for calculating these values geothermal heating and cooling system. However, there are multiple other methods of analyzing these systems. One common method involves approximating the specific heat as a constant value for the entire system (4) (5). The method presented in this project differs by taking into account the variations of thermal conductivity for each element in the system. Other methods approximate the system using 3-dimensional finite element analysis, where the program used in this report approximates things as a 2-dimensional plane that is evenly rotated around a center point. This approach is valid for a horizontal loop pipe. This type of pipe has the majority of its mass below the point where surface interactions can affect the system. However, for a vertical loop system this approach is not valid and 3-dimensional finite element analysis must be done to properly approximate the system and its response. A method for this is presented in <u>Efficient finite element formulation for geothermal heating systems. Part II: Transient</u> (6). In this paper they discuss a similar method as the one presented in this program. The major difference is the use of a 3-dimensional procedure as opposed to the 2 dimensional procedure used here. The procedure presented in the paper is designed for a vertical closed loop system.

3 EXPERIMENTAL INTRODUCTION

For this experiment multiple variables were changed while keeping everything else constant. This was in an effort to see how each one of these variables affected the geothermal system. These variables were changed over a wide range (wider than what is seen in nature) to get an understanding of the upper and lower bounds of their effect. These variables will be compared to how they change with respect to the normal system and how they change over their range. The variables changed and their normal values are given in **Error! Reference source not found.**.

Variable	**Value**
Earth Specific Heat	1900 J/kg-C
Earth Thermal Conductivity	1.0 W/m-C
Pipe Thermal Conductivity	0.12 W/m-C
Inner Pipe Diameter	0.025 m
Pipe Length	45.0 m
Fluid Velocity	1.2 m/s

Table 1. Initial Values

These values represent common values for these variables and will be taken as the normal variable set to compare against.

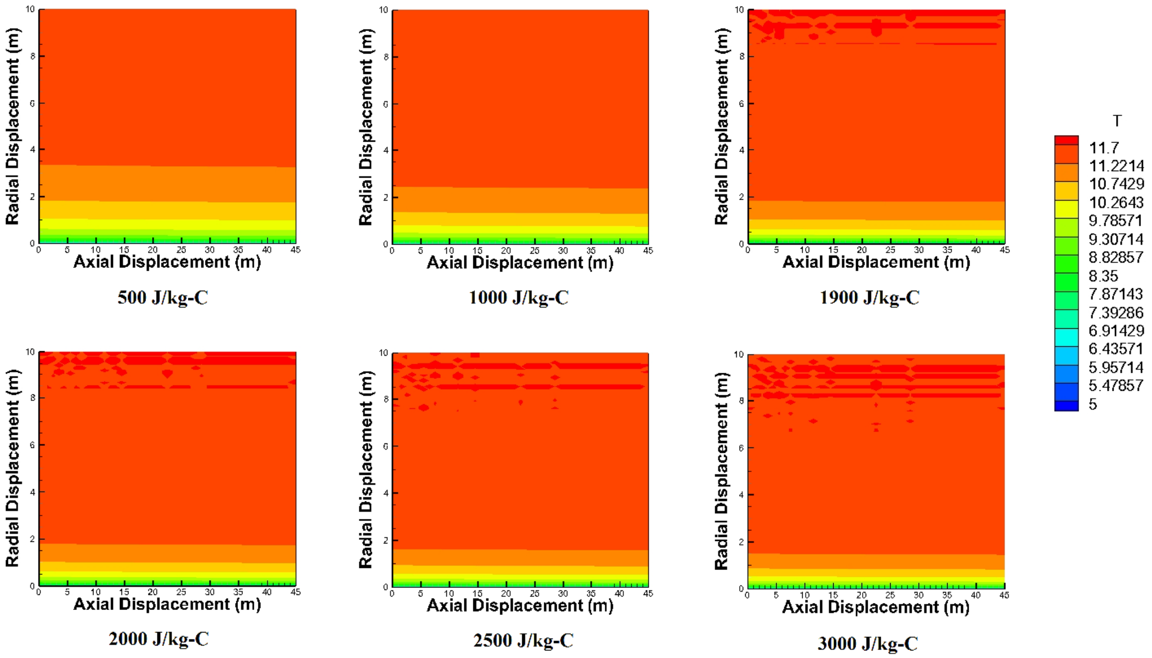
4 RESULTS

Below is the data obtained from varying each variable. The simulation was run as a heating cycle for a 6 month period. In this cycle, energy is being pulled from the surrounding earth and stored in the water. This will lead to a drop in temperature of the surrounding earth and an increase in temperature of the water. What will be focused on is the temperature distribution of around the pipe as a function of the variable being tested as well as the exit temperature of the water and the amount of energy flowing into the water as a function of time.

4.1 Earth's Specific Heat

4.1.1 Temperature Distribution

One of the first variables tested was the specific heat of the surrounding earth. Figure 4 below shows the temperature profile of the ground surrounding the pipe for various values of the specific heat of the earth. It can be seen from the graphs that as the value for specific heat increases, there is a noticeable drop in the amount of surrounding earth that loses energy to the flowing water. This can be interpreted that as the value of specific heat increases, the earth is able to store more energy. This can equate to more energy that can be used for the geothermal system.



500 J/kg-C

1000 J/kg-C

1900 J/kg-C

2000 J/kg-C

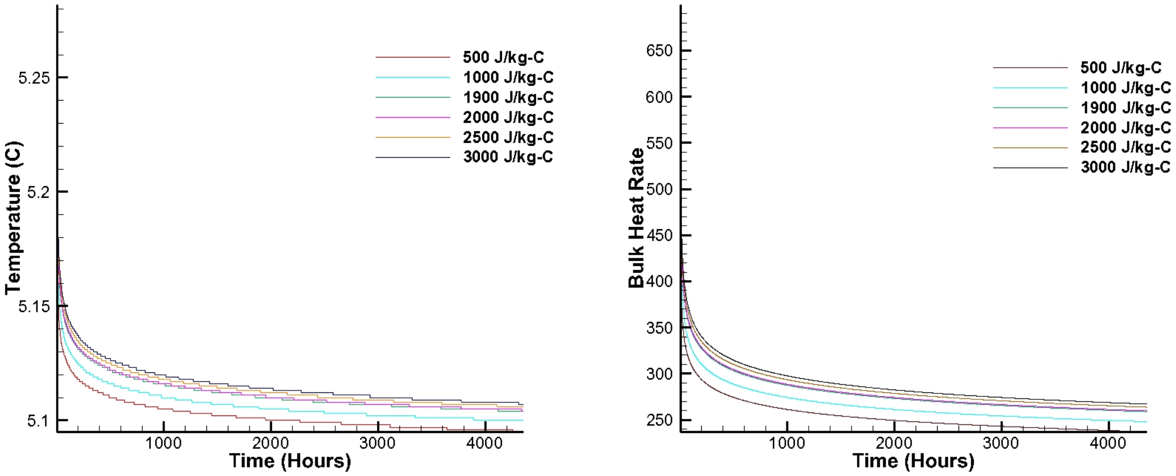
2500 J/kg-C

3000 J/kg-C

Figure 4. Ground Temperature at 3 Months for Varying Earth C_p

4.1.2 **Water Exit Temperature and Energy in Over Time**

One of the most important parameters to know about when designing a geothermal system is the temperature that the water is going to be entering the heat pump at. Figure 5 below shows what happens to the exit temperature of the water both as a function of time and for the various specific heats of earth that were tested. It can be seen that over time, the temperature of the water greatly drops off and more closely approaches the 5°C temperature that it entered the pipe at. This is because as time goes on there is less and less energy in the surrounding soil. This means there is less energy that can go into the water, a claim that is backed up by the second part of Figure 5. This shows the relative amount of energy that is going into the water over time. It is seen that the amount of energy that is entering the system is high at first, but gradually drops off just like the temperature. If a system were only used for heating, like the case here, it is possible that there would be a total loss of energy in the surrounding earth and the system would no longer be able to increase the temperature of the water as needed. However, this only represents half of a year's cycle. In most places the other half would be used for cooling. Running the system in this way would put energy back into the surrounding ground. This energy could then be used again when the heating cycle was needed.



Water Exit Temperature Over Time

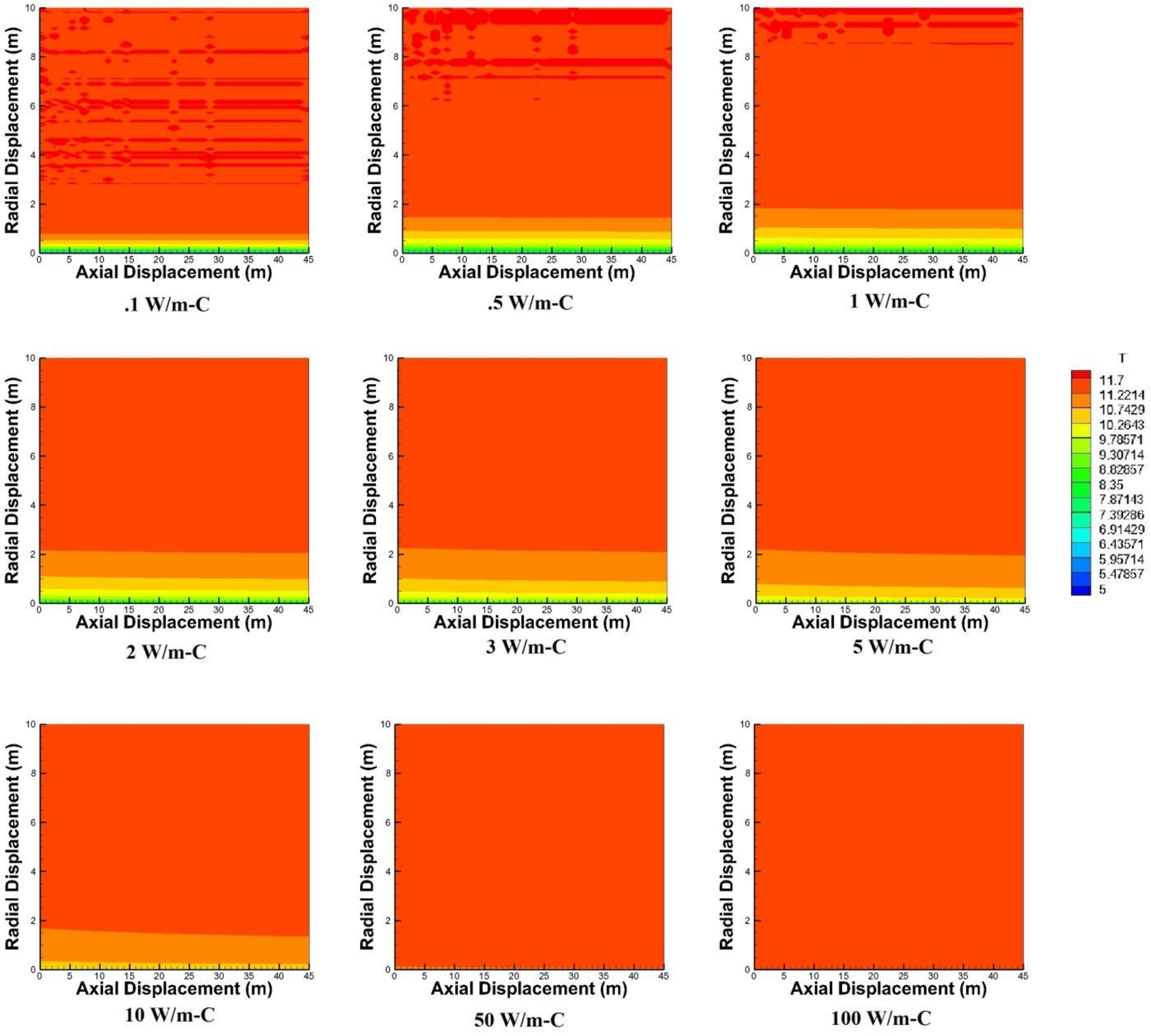
Heat Rate Into Water Over Time

Figure 5. Water Temperature and Heat Rate v. Time For Varying Earth C_p

4.2 Earths Thermal Conductivity

4.2.1 Temperature Distribution

Nine separate values were tested for the thermal conductivity of the earth. The values ranged from .1 W/m-C to 100 W/m-C. The temperature distributions for these values are shown below in Figure 6.



.1 W/m-C

.5 W/m-C

1 W/m-C

2 W/m-C

3 W/m-C

5 W/m-C

10 W/m-C

50 W/m-C

100 W/m-C

Figure 6. Ground Temperature at 3 Months for Varying Earth K

When varying the thermal conductivity of the earth, a very interesting trend happens to the temperature distribution. As shown in Figure 6, the variation in temperature around the pipe is reduced to a very small area, this area increases with an increase in thermal conductivity until around 5 W/m-C, then this area of variation decreases until it is almost non-existent around 50 - 100 W/m-C. Also, it can be noted that the lower values for thermal conductivity have a wider range of temperatures in that band. This is due to the fact that as the thermal conductivity of the earth increases, it is easier for energy to flow through the soil. This freedom of motion allows a near even distribution of energy throughout the entire section of the ground that was investigated.

4.2.2 Water Exit Temperature and Energy Over Time

Again, the temperature at which the fluid was leaving as well as the energy absorbed by the fluid over time was looked at. Figure 7 below shows that the temperature and energy absorbed follow the same trend. Also, it is seen that with an increase in the thermal conductivity of the earth there is also an increase in the temperature the temperature is leaving the pipe. Also, as the thermal conductivity of the earth increases there is a noticeable change in the amount the temperature drops over time. A higher value of thermal conductivity can provide a more constant fluid temperature for the duration that heating would be used.

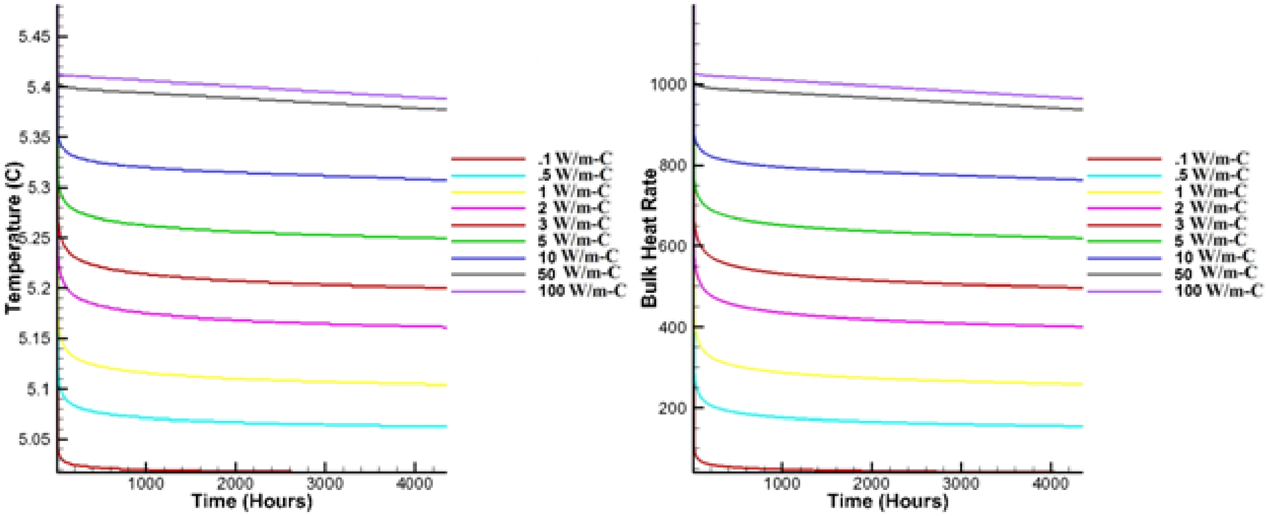
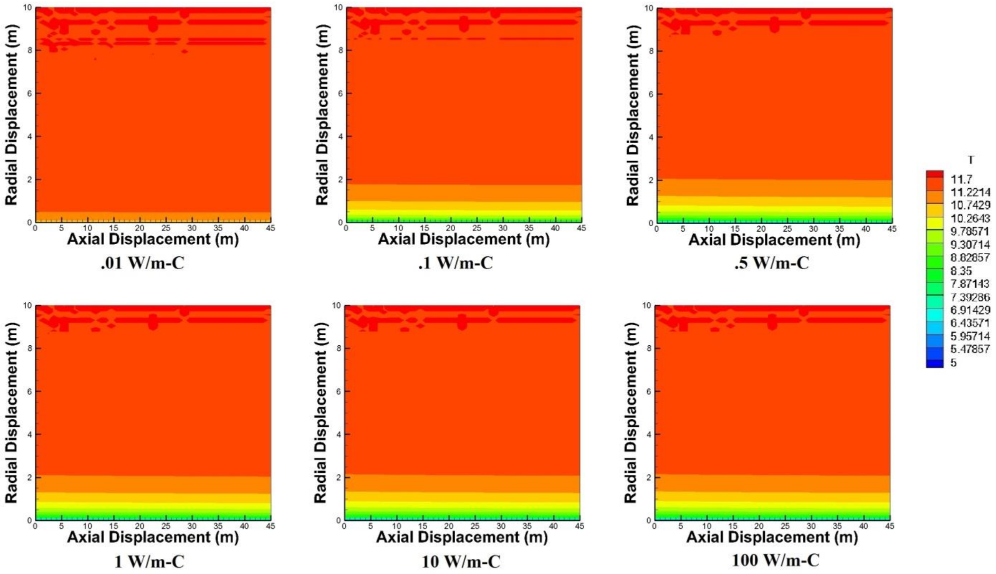


Figure 7. Water Temperature and Heat Rate v. Time For Varying Earth K

4.3 Pipe Thermal Conductivity

4.3.1 Temperature Distribution

The thermal conductivity of the pipe was also looked at. Figure 8 below shows the temperature distribution for values of .01 W/m-C to 100 W/m-C. From Figure 8 it can be seen that anything past .5 W/m-C looks the same as far as the temperature distribution of the surrounding earth. This shows that since the thermal conductivity of the tube does not have as much of an effect on the surrounding earth as other properties, especially properties of the earth itself. From Figure 8 it is seen that only small values for thermal conductivity of the pipe seem to have a great effect on the temperature of the surrounding earth. This is due to the fact that a low value of thermal conductivity does not allow much heat transfer to occur. This phenomenon is also seen in the temperature and energy graphs in Figure 9. One reason for the pipes lack of influence could be due to the thickness of the pipe. Relative to everything else in the system, the pipes thickness is small.



.01 W/m-C

.1 W/m-C

.5 W/m-C

1 W/m-C

10 W/m-C

100 W/m-C

Figure 8. Ground Temperature at 3 Months for Varying Pipe K

4.3.2 Water Exit Temperature and Energy Over Time

The graphs of Temperature and Energy vs. time shown in Figure 9 show what is expected from looking at the temperature distributions in Figure 8. When the thermal conductivity of the pipe is lowest, that is when there is the least amount of energy entering the system. Also, this is where the temperature remains closest to the initial fluid temperature of 5 °C. Also seen on the graph, as the value increases, the lines approach the same values to the point where the lines for 10 W/m-C and 100 W/m-C are the same at this scale. This again illustrates how little impact the thermal conductivity of the pipe has for any value over .5 W/m-C. However, in our case we are taking the initial value of the pipes thermal conductivity to be .12 W/m-C. This value would closely follow the line for .1 W/m-C in the figure below. This means that there could be an improvement for the temperature that the fluid leaves at if the pipe with a higher thermal conductivity was chosen.

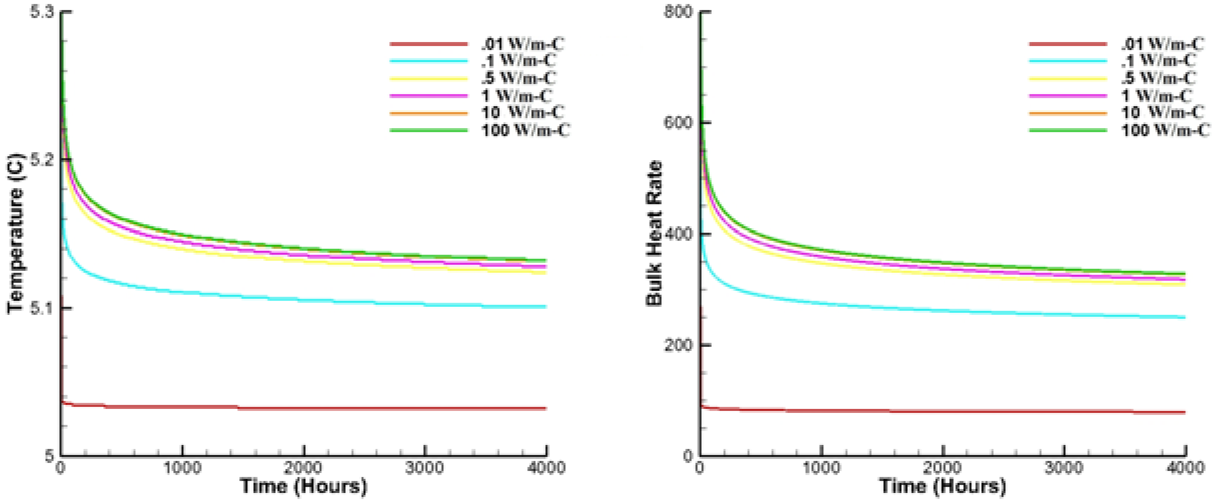


Figure 9. Water Temperature and Heat Rate v. Time For Varying Pipe K

For the pipe conductivity, another way of looking at this data is to look at how the thermal resistance of the pipe changes with a varying thermal conductivity. The basic equation for thermal resistance is due to conduction in a cylinder:

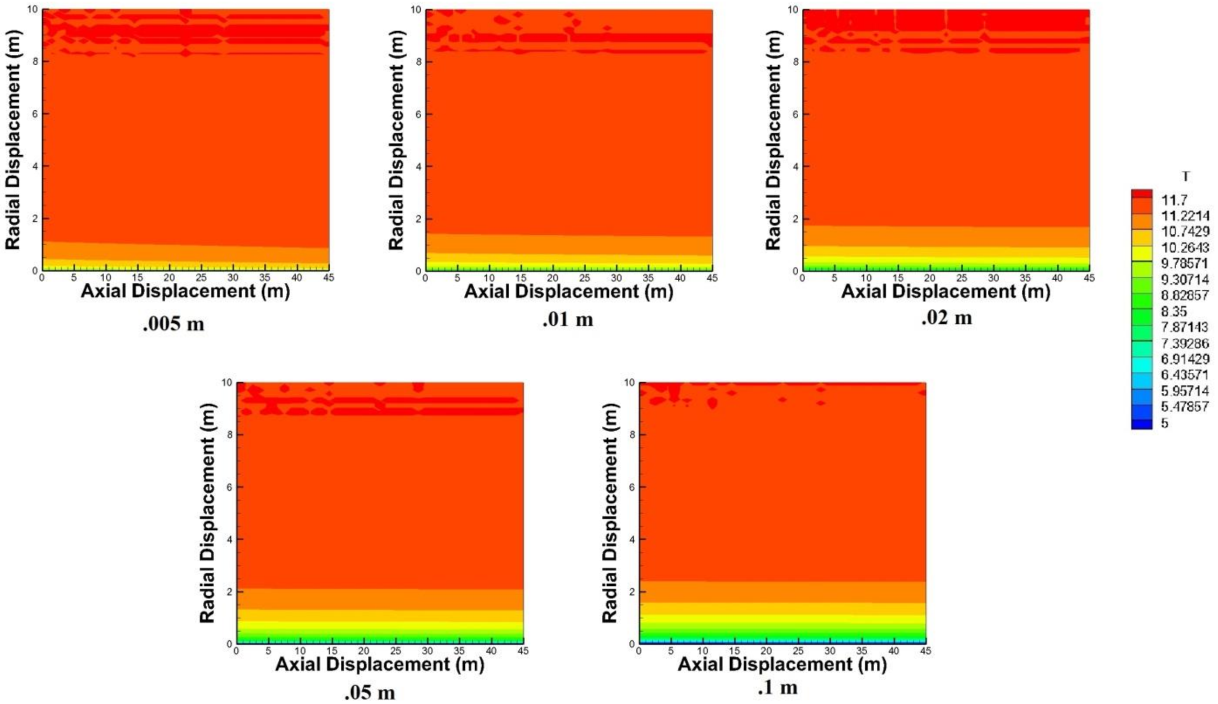
$$R_{cond} = \frac{\ln(r_o/r_i)}{2\pi kL}$$

Where, r_o and r_i are the outer and inner radii respectively, L is the length of the pipe and k is the thermal conductivity of the pipe (7). From this relation it can be seen that since thermal conductivity is in the denominator, resistance increases as thermal conductivity decreases. This reflects the data obtained, because smaller values for thermal conductivity yielded smaller values for both temperature and bulk energy out. This means there was more resisting the flow of energy into the water, corresponding to the higher thermal resistance of the pipe.

4.4 Pipe Diameter

4.4.1 Temperature Distribution

Five different pipe diameters were tested to see the effect on the system. The diameters ranged from 5mm to 10cm where a normal pipe diameter is around 2.5cm. Pipe diameter will affect the both the amount of fluid flowing through the system as well as the surface area that the fluid is in contact with the pipe and that the pipe is in contact with the earth. Figure 10 below shows the thermal distribution at 3 months for the 5 pipe diameters tested. From Figure 10 it is seen that as the pipe diameter increases in size, so does the area around the pipe that is affected by the temperature. This makes sense because as the pipe diameter increases, the amount of fluid flowing increases (since average velocity is kept the same). More fluid requires more energy to heat up. This is also demonstrated in Figure 11.



.005 m

.01 m

.02 m

.05 m

.1 m

Figure 10. Ground Temperature at 3 Months for Varying Pipe D

4.4.2 **Water Exit Temperature and Energy Over Time**

Unlike the other parameters discussed so far, temperature and energy have an inverse relationship when the diameter of the tube is varied. This phenomenon is illustrated in Figure 11. The 5mm diameter pipe is able to achieve the highest temperature and absorbs the least amount of energy whereas the 10cm pipe absorbs the most energy but does not get much higher than the initial 5 °C. This is due to the fact that there is more mass flowing through the pipe increases as the diameter increases. This is because that in this simulation the average velocity of the fluid in the pipe was kept constant. However, although a smaller diameter pipe is able to achieve higher temperatures using less energy, it would not be able to supply an adequate water flow for the heat pump.

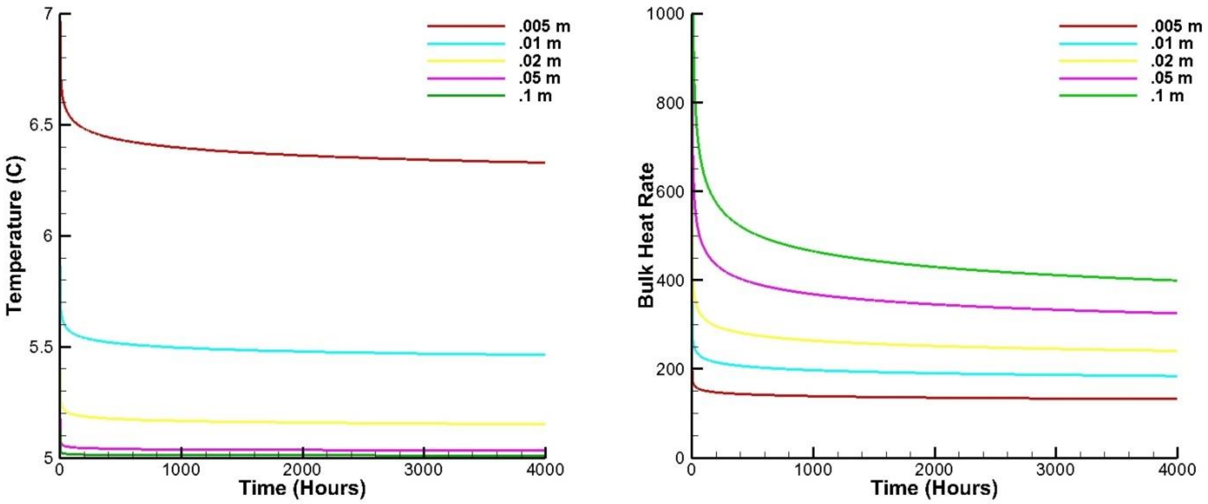
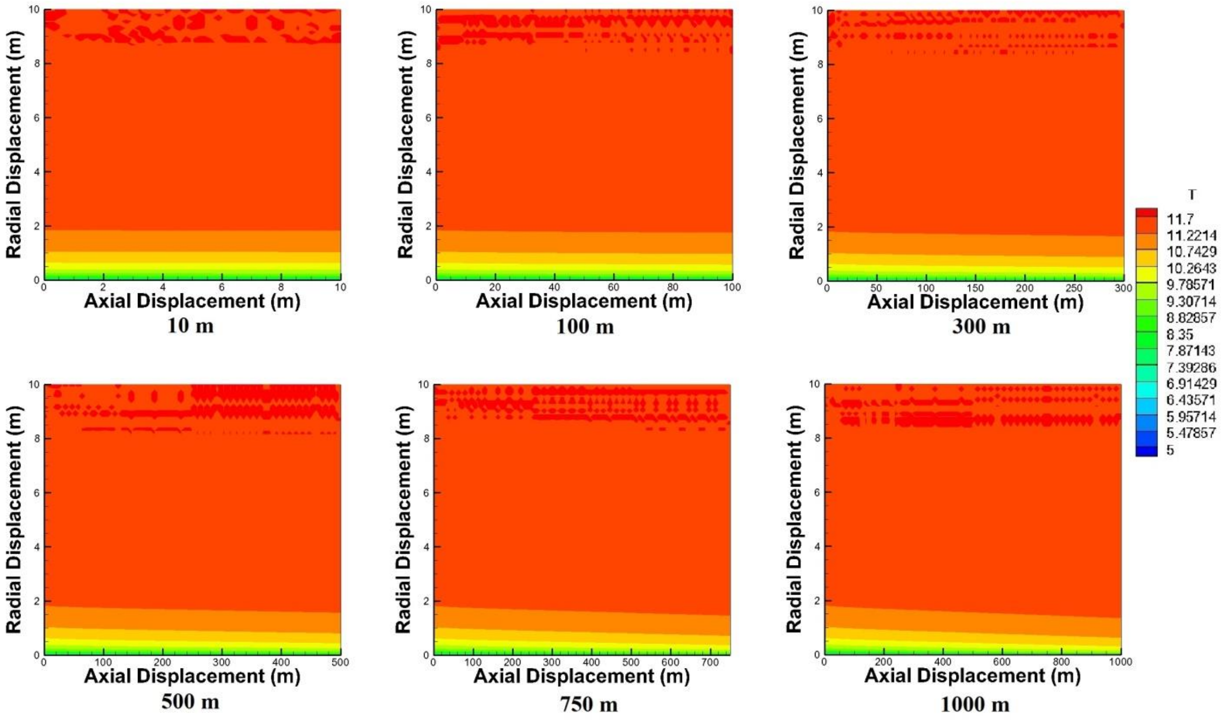


Figure 11. Water Temperature and Heat Rate v. Time For Varying Pipe Diameter

4.5 Pipe Length

4.5.1 Temperature Distribution

Six different values for pipe length varying from 10m to 1000m were also tested. Figure 12 illustrates the temperature distribution in the surrounding earth. From the figure, it is seen that the temperature distribution does not change much from 10m to 1000m. However, what can be seen is the effect of the flow over a longer distance. Looking at the plot for 1000m, a decrease in the distance of the affected area can be seen along the length of the pipe. This makes sense as the fluid starts to gain energy as it first enters the pipe. This means that as it travels along the length of the pipe it needs to absorb less energy. This leaves more energy in the earth along the length of the pipe keeping it at a higher temperature.



10 m 100 m 300 m

500 m 750 m 1000 m

Figure 12. Temperature at 3 Months for Varying Pipe Length

4.5.2 Water Exit Temperature and Energy Over Time

The temperature and energy over time as the pipe length increases behaves as expected. This is shown in Figure 13. A pipe length of 1000m is able to achieve a higher average temperature than a pipe of 10m length. Being able to achieve varying temperatures just by changing the pipe length is a positive outcome. The pipe length is a parameter in the system that is very easily changed. Most closed loop systems can easily be adapted for more pipe length; this can be achieved by simply adding more loops to a horizontal system or digging another trench for a vertical loop system. However, this simulation was done assuming a straight length of pipe with no interference from any other pipe that might be in the area. For a more accurate estimate on a design that uses a loop another simulation would have to be run with this interference in mind.

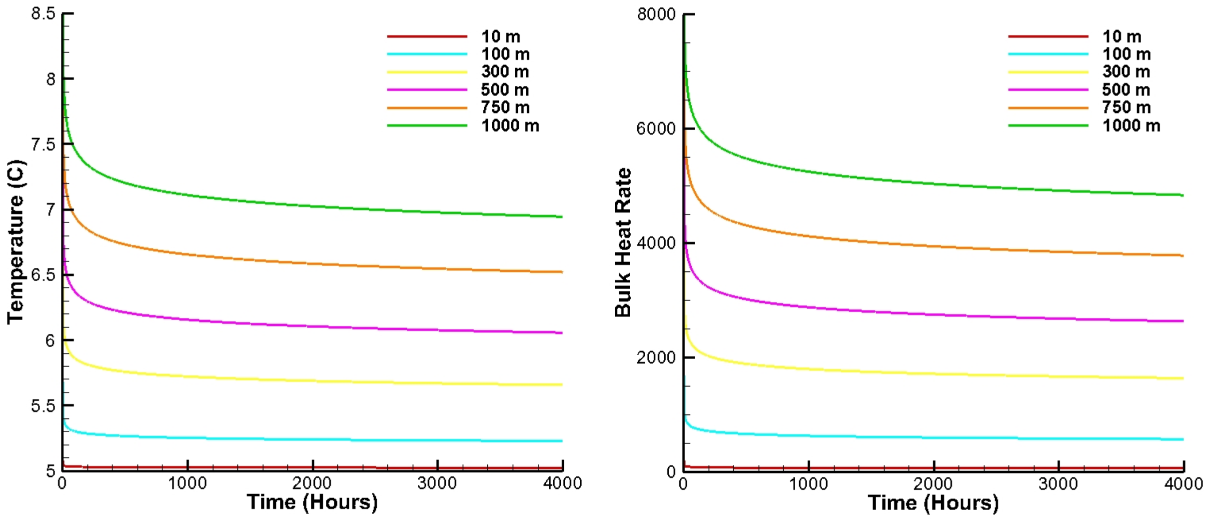
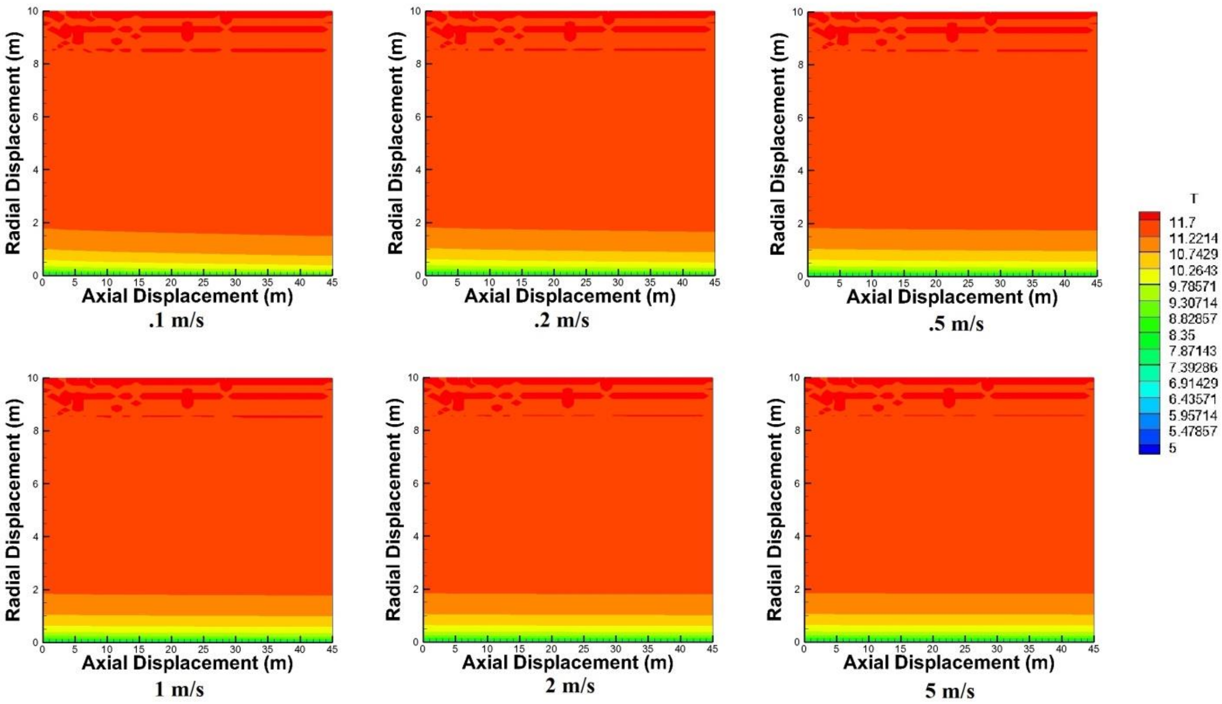


Figure 13. Water Temperature and Heat Rate v. Time For Varying Pipe Length

4.6 Fluid Velocity

4.6.1 **Temperature Distribution**

Six values for average fluid velocity were tested ranging from .1m/s to 5m/s. As with varying lengths before there does not seem to be much of a difference between the varying velocities. However, looking at the temperature distribution of a velocity of .1m/s a profile similar to that of the 1000m length run can be seen. This is because slowing the velocity down essentially does the same thing and that is keep the fluid in contact with the pipe and earth for a longer period of time. However, unlike varying the pipe length, varying the average flow speed greatly impacts the flow rate which could adversely affect the output of the heat pump.



.1 m/s .2 m/s .5 m/s

1 m/s 2 m/s 5 m/s

Figure 14. Temperature at 3 Months for Varying Fluid Velocity

4.6.2 **Water Exit Temperature and Energy Over Time**

Figure 15 below shows that increasing the velocity of the fluid has the opposite effect on the temperature as extending the pipe length. This similarity makes sense since extending the pipe increase the time that the water is in the pipe. Where conversely, increasing the average velocity of the fluid decreases the amount of time the fluid is in the pipe. However, unlike how increasing the pipe length increases both the temperature and the bulk heat rate out; increasing the velocity has an inverse effect. It can be seen that as velocity increases, the bulk heat rate out rises, even though the exiting temperature of the water is decreasing. This is due to the increased mass flow rate. Even though the fluid may be absorbing less energy per certain volume, the increased flow rate has a greater effect on the bulk heat rate out.

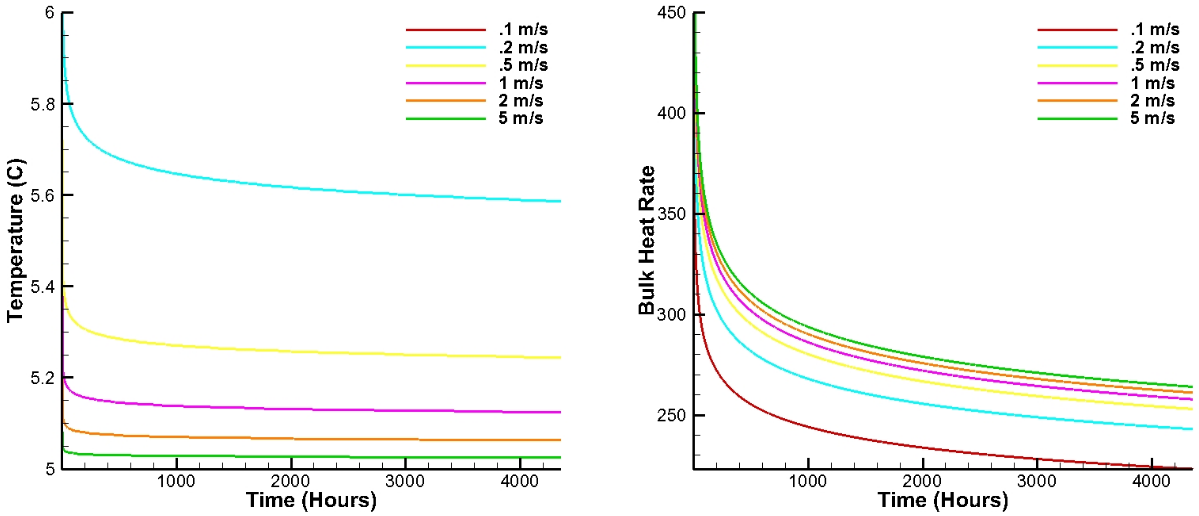


Figure 15. Water Temperature and Heat Rate v. Time For Varying Fluid Velocity

5 CONCLUSION

The purpose of this report was to investigate the effects of various parameters on a geothermal heat pump. All this data was obtained using the same program that solved a 2-dimensional heat transfer problem. The above results may not represent possible operating conditions found in nature, but do illustrate the effects the chosen parameters have on the system.

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