Analytical Model for a Modular Geothermal System

A Major Qualifying Project Report Submitted to the Faculty of WORCESTER POLYTECHNIC INSTITUTE in partial fulfillment of the requirements for the Bachelor of Science by:

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March 22nd, 2018

Approved: _______________________________

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Advisor: Christopher Scarpino, Ph.D.

Project Number: <ME-XXX-0000>

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Prof. Robert Daniello, Major Advisor

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Prof. Christopher Scarpino, Co-Advisor

Acknowledgments

Our Major Qualifying Project team would like to extend a special thanks to our advisors throughout the project, Professor Robert Daniello and Professor Christopher Scarpino for their constant support and help with the technical and analytical aspects of the project.

We would also like to thank all of the professors at Worcester Polytechnic Institute that we utilized for their advice and expertise, the rapid prototyping department for making our 3D model possible, and the students at the writing center that helped us to convey our ideas and results through our final project report.

Lastly, we would like to thank the students who worked on the Major Qualifying Project in 2017 titled *Modular Geothermal Heat Pumps.* Without their research, ideas, and code foundation, our project would not have advanced the way it did.

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Abstract

A geothermal heat pump system is a renewable energy source that uses earth's ground temperature to regulate the temperature of a building. The focus of this study was to design a modular ground heat exchanger unit for a heating system located in New England. This design used well technology to account for the low ground temperatures of the region. The Engineering Equation Solver program was used to build a model, which was created to calculate the thermal resistance and energy transferred thru the model. The model was then iterated to determine how the energy output changes. Through analysis, the final design optimized the system yield. In result, the final design of the system reduced the size and increased the efficiency of installation of the ground portion of the system.

Introduction

Earth's natural geothermal sources have been used as a valuable resource for over 10,000 years. The use of natural resources started with the American Paleo-Indians, who used water from hot springs for cooking, bathing, and cleaning ("History of Geothermal Energy", n.d.). The first industrial use of geothermal energy began in Italy in the late 18th century. It was not until the 1960s when Pacific Gas and Electric developed the first large scale geothermal power plant that geothermal power plants became significant in the United States (US). This first plant was built in San Francisco, which produced 11 Mega Watts. Due to its success, geothermal heat pumps started to gain popularity within the US during the 1980s. Even though the US was among the first few countries to use geothermal sources as an energy resource, Iceland is the modern leader of this industry.

Geothermal technology is a form a renewable energy that uses earth's natural ground temperature to assist in regulating a building's temperature, in a method less direct then the original American Paleo-Indian use of hot springs. This technology uses a series of pipes underground full of liquid to collect the earth's natural heat and transfer it above ground to the heat pump system which includes a heat exchanger. It is noteworthy that the earth's soil remains at fairly constant temperatures at various depths below the surface. This provides a consistent thermal reservoir to which a heat pump cycle can be designed, eliminating the cold temperatures that otherwise limit heat pump performance. When that energy is brought into the building it reduces the energy needed to heat or cool a building to the desired temperature. The heat pump system works to move the natural heat energy of the earth into a building to be used for domestic heating.

The first major roadblock for the geothermal energy industry within the United States was the lack of awareness of the overall concept of geothermal heating ("Geothermal heat pump tax credits reinstated", 2018). Due to the complexities of drilling and collecting this natural energy, residential use of this technology has yet to expand within the US markets. The primary issue of the industry is that the general population is not aware of the option or the benefits of installing a geothermal energy heating system within their homes. Often, geothermal heat pumps have a large upfront cost due to the complex installation of the system. However, despite the initial high cost, the overall cost to maintain the system over its lifetime is lower with a payback period of about 12-13 years, depending on the country and environment ("Geothermal heat pump tax credits reinstated", 2018). For example, during the Obama administration, the United States Federal government, along with a variety of states, offered a variety of tax incentives and tax credits to help offset the initial cost of a new geothermal system. Even with these new tax incentives, the use of geothermal energy is still uncommon in the US due to the cost and complexity of the system. Despite the lack of resources for geothermal energy within the United States, data and information from the world's leading user, Iceland, can be adapted to help understand how a geothermal heat pump system would work in the United States.

The project mission is to further develop a concept for a modular ground unit heat exchanger for a geothermal heat system for residential usage. The modular ground heat exchanger unit for the system is referred to as "the pod" and will be modelled for use in the United States. Heat extracted from this portion of the system supplies the heat pump cycle. The project objectives are to improve the mathematical model from the 2017 Major Qualifying Project (MQP) titled *Modular Geothermal Heat Pumps and* develop a new geothermal heating system concept. These objectives will be accomplished using Engineering Equation Solver Software (EES) to complete numerical calculations.

BACKGROUND

The following section contains relevant information needed to design and complete this project. This information explores Iceland’s modern geothermal technology, the modern geothermal systems in the United States, the geothermal heat pump system, the materials of a geothermal system (including pod materials, pipe materials, pipe fluids, and surrounding mediums), the International Ground Source Heat Pump Association, and a model for the ground temperature estimations. This section concludes with an examination of the future of geothermal technology.

ICELAND'S MODERN GEOTHERMAL TECHNOLOGY

Although the United States does not consider the use of geothermal technology a priority, there are other countries that consider geothermal energy a primary resource. For example, 72% of Iceland’s energy is renewable; approximately 85% of the country’s homes are heated with geothermal energy, which also provides roughly 18% of the country’s electricity (Motavalli, 2008). This makes Iceland the world’s leading user of renewable energy, and geothermal energy is particularly popular due to the location of the island. Iceland happens to be located where the North American and Eurasian plates meet, just south of the Arctic Circle. In geological terms, this is called a “hot spot”. Iceland has over 20 active volcanoes and over 600 hot springs due to its location (Ragnarsson, 2015). Since the Late Mesozoic Era, these two plates have been separating, causing uplift in the lithosphere layer of the earth’s crust and the creation of high and low temperature fields shown in Figure 1. This is an example of a direct geothermal system, as the energy is drawn directly from a hot spot. The excessive amount of heat just below Iceland's thin surface makes the country an ideal candidate for geothermal energy and heating technology.

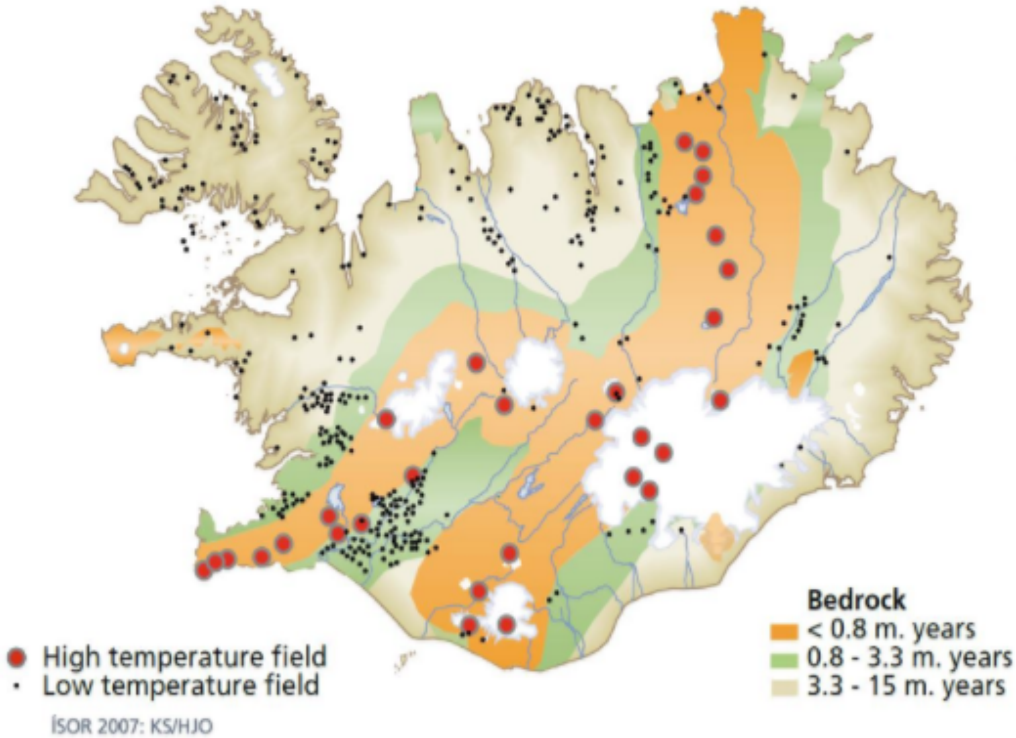


FIGURE 1: VOLCANIC ZONES AND GEOTHERMAL AREAS IN ICELAND[1]

There are 7 major power plants in Iceland that produce geothermal energy: Krafla, Svartsengi, Bjarnarflag, Nesjavellir, Husavik, Reykjanes, and Hellisheioi. Together, these plants are estimated to produce 5,293 GWh per year (Ragnarsson, 2015). In Krafla, where 480 GWh/yr is produced, a well exists that is the hottest well in the world. This provides the country with near-magma geothermal resources. Temperatures exceed over 400 degrees Celsius and pressure exceeds over 100 bar (Markusson, 2015). A conventional well built in Krafla, Iceland (Figure 2) is a common well style used for geothermal heat extraction. The United States is looking to

[1] Image taken from "Geothermal Development in Iceland 2010-2014" (Ragnarsson, 2015).

harvest the energy of the ground without the use of natural hot spots because there are fewer hot spots in the United States, primarily located in Hawaii and Yellowstone. The United States has fewer hot spots, and thus does not have as much access to direct systems. However, using a well as an energy reservoir could be used to harvest the energy from the ground without these hot spots. The energy would then serve as the thermal reservoir for a heat pump system allowing for building heating at reasonable temperatures.

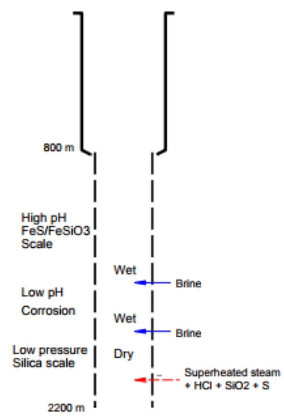


FIGURE 2: CONVENTIONAL KRAFLA WELL[2]

MODERN GEOTHERMAL SYSTEMS IN THE UNITED STATES

Within the United Sates, manufacturers offer many similar types of geothermal heat pump systems. The most common types in industry currently are the horizontal, vertical, and well water systems. The average cost to install these systems is approximately $25,000 for a 60,000 BTU heating load of a 2,500sq-ft home. The lifetime of systems can be 18-23 years, almost double the conventional system ("Energy Environmental", 2018).

The modern standard for a geothermal System is consisted of a series of pipes that are laid underground. The system functions by moving the energy from the warmer soil underground to either heat or cool a building. The pipes underground cycle fluid that is then passes throughout

[2] Image taken from "Utilization of the Hottest Well in the World, IDDP-1 in Krafla" (Hauksson & Markusson, 2015).

the entire geothermal system including the pipes in the ground and the house's HVAC system. Once the liquid reaches the above ground HVAC unit, the unit uses a heat pump cycle to extract energy from (or release energy to) the ground, thereby conditioning the air to the desired temperature. Heat pump cycles are capable of high coefficients of performance, meaning they are more efficient than using direct electric heat. Once the desired temperature is reached, the HVAC system releases the new tempered air throughout the building.

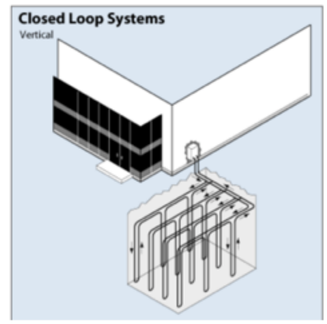


FIGURE 3: VERTICAL CLOSED LOOP SYSTEM

The modern standard for a geothermal system consists of a series of pipes that are laid underground. The overall goal of the system is to take advantage of the consistent temperature from the soil underground to either heat or cool a building. The pipes are underground, full of a liquid, and cycle throughout the entire geothermal system. This includes the pipes in the ground and the house's HVAC system. Closed-looped systems can be built in two directions vertical as shown in Figure 3, and horizontal as shown in Figure 4[3]. The vertical loop system places a series of pipes deep into the ground to reach higher temperatures which is typical of buildings with larger energy needs. The horizontal loop system places the pipes flat across a yard or underneath a parking lot. Typically, a horizontal system is the most common method used in residential buildings. A closed-loop system requires a significant installation cost due to the large excavation site where these loops are placed and installed.

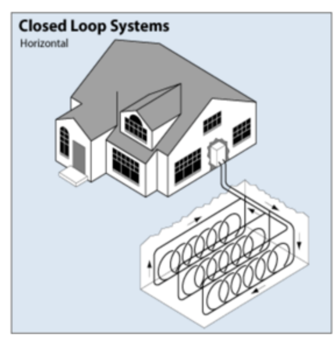


FIGURE 4: HORIZONTAL CLOSED LOOP SYSTEM

[3] Figures 3 and 4 were taken from energy.gov ("Geothermal Heat Pumps", 2017).

The open-loop geothermal system is only used when an underground water source is located near the building ("Geothermal Heat Pumps", 2017). Open-loop systems function by taking water from a larger source that is already at the desired temperature, and then using this tempered water as the baseline temperature for the above ground system. Common water sources consist of local wells and underground water tables. These sources of underground water are ideal to use since they are often very deep and maintain stable year-round temperatures. Another major open-loop water source can be a nearby pond or lake. In this variation of the system, the pipes would lay approximately 8ft below the water's surface within the body of water. In all open-loop systems, there are many environmental concerns about the pipes eroding over time and leaking dangerous minerals into the ground water. Overall, open-loop systems are typically less common due to the unpredictable nature of the water. Although open-loop systems are less common, a variation of these systems would provide a home with more energy than a closed-loop system. If the pipes were made out of a corrosive resistant material, then open-loop systems would be safer, and could become more commonly installed.

The Geothermal Heat Pump

The standard geothermal heat pump machine consists of a compressor, heat exchanger, and a series of controls. When the system is in the heating mode, the refrigerant passes through the heat exchanger where it absorbs the heat from the fluid that come from the pipes underground. The traditional HVAC system then adds more heat if needed to the current ground-tempered air. After the air reaches the desired temperature, it is then circulated throughout the air ducts within the home ("Geothermal HVAC Systems", 2017).

Figure 5 demonstrates the ideal model depiction of a geothermal heat pump system. It takes advantage of the water in an already existing well, which will be explored further along in the paper.

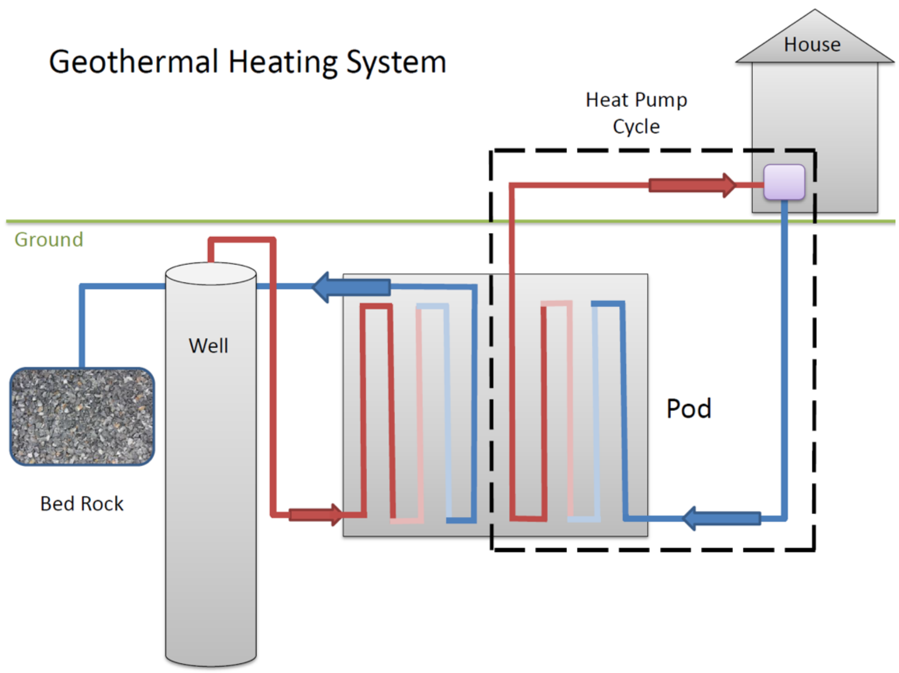


FIGURE 5: GEOTHERMAL HEAT PUMP DIAGRAM

A large portion of geothermal energy is the relationship between the loops of the geothermal system and the composition of the dirt in the ground. Certain rocks and soils have much better thermal conductivity than others, which allows for geothermal systems to work better in those specific environments. Thermal conductivity of the ground is determined by thermal properties of the soil content and the moisture levels in the soil. These factors greatly affect the heat transfer from the ground to the pod (Cristina Sáez Blázquez, Arturo Farfán Martín, Ignacio Martín Nieto, & Diego Gonzalez-Aguilera, 2017).

Geothermal technology has many benefits that make it a strong alternative to fossil fuels. The main benefit of geothermal energy is that it causes minimal pollution to the environment and is renewable along with wind/solar electric sources. Geothermal systems are very effective for both heating and cooling systems because they can be used as heat sinks or heat sources, which gives them their high coefficient of performance.

Materials of a Geothermal System

The materials used in the design of a geothermal heat pump system affect the overall efficiency of the model. The pod and pipe material can help achieve optimum heat transfer between the ambient environment and the pod; the pod and the surrounding fluid; the surrounding fluid and the pipes; and the pipes and the flowing fluids. For both pod and pipe material, different families of materials were considered with regard to their mechanical properties, thermal properties, and cost. These include metals, plastics, composites and fiber reinforced materials. The pipe fluid choice and selected medium surrounding the piping can also help maximize heat transfer. Brines, refrigerants, and water were explored for the working fluid, and different phase-changing materials and groundwater were analyzed for the surrounding medium. Proper selection of the surrounding fluid, pipes, and pod material, will lay the groundwork for an effective and efficient heat pump design.

Exploring Pod Materials

The first material to consider in the system design is the pod material, which encapsulates the piping configuration and is filled with a liquid. For the purpose of this study, the liquid that will fill the rest of the pod and submerge the pipes will be called the "surrounding medium". Many different materials were considered for the outer pod material: concrete (a composite material), metallic alloys, plastics, reinforced materials utilizing glass, carbon, or metal fibers, and polymers. Table 1 below shows the 21 different materials analyzed for this purpose. The table is sorted by thermal conductivity, with the higher thermal conductivities at the top of the table and the lower thermal conductivities at the bottom of the table. This parameter was sorted because the thermal conductivity of the material is the property which describes how much heat is moving through the material. This is essential to the efficiency of the system, because increased heat transferred through the material increases the heat that is transferred to the home overall.

Pod Material	K [W/m-K]	C (J/kg-°C)	Processed easily?	Strength (MPa)	Density (10^3 kg/m^3)	Durability	Cost (USD/kg)
Copper Alloys	380-400	372-388	Yes	30-500	8.93-8.94	Acid, corrosion resistant	6.4-7.1
Aluminum Alloys	76-235	857-990	Yes	30-500	2.5-2.9	Acidic deformation	2.21-2.53
Stainless Steel	12.0-24.0	450-530	Yes	170-1000	7.6-8.7	Corrosion resistant	5.61-6.1
Concrete	0.8-2.4	835-1050	Yes	1.0-3.0	2.3-2.6	Difficult to remove	0.04-0.06
PC (20% C)	0.51-0.531	1470-1530	Yes	99.2-110	1.27-1.29	Acid resistivity	7.78-8.62
ABS (20% carbon)	0.386-0.418	1600-1660	Yes	82.4-88	1.13-1.14	Weak acid resistivity	6.94-7.95
PVC (20% glass)	0.379-0.394	1330-1390	Yes	47.4-70.6	1.43-1.5	Acid resistivity	1.92-2.12
ABS (40% aluminum flake)	0.295-0.306	1270-1320	Yes	22.8-29	1.54-161	Weak acid resistivity	2.71-2.99
Polyester (unfilled)	0.287-0.299	1510-1570	Yes	33-40	1.04-1.4	Acid resistivity	3.84-4.3
ABS (7% stainless steel)	0.276-0.287	1610-1670	Yes	31.5-34.7	1.11-1.13	Weak acid resistivity	3.22-3.66
ABS+PVC blend (unfilled)	0.264-0.275	1540-1610	Yes	29.6-44.8	1.13-1.25	Weak acid resistivity	3.23-3.85
PC (10% glass)	0.218-0.318	1470-1530	Yes	58.6-69	1.27-1.28	Weak acid resistivity	3.85-4.09
ABS+PC (unfilled)	0.262-0.272	1400-1500	Yes	24.1-51	1.07-1.15	Weak acid resistivity	3.29-3.57
ABS (unfilled)	0.253-0.263	1690-1760	Yes	34.5-49.6	1.03-1.06	Weak acid resistivity	2.4-2.84
PC (30% glass, 2% silicon)	0.176-0.289	1340-1390	Yes	84-92.8	1.45-1.47	Weak acid resistivity	3.64-4.03
PVC (unfilled)	0.147-0.293	1360-1440	Yes	35.4-52.1	1.3-1.5	Acid, corrosion resistant	1.4-1.6
PMMA (unfilled)	0.17-0.25	1400-1520	No	57.8-63.7	1.18-1.2	Weak acid resistivity	2.76-2.87
ABS (20% glass)	0.193-0.209	1530-1600	Yes	57.9-71.7	1.18-1.22	Weak acid resistivity	2.76-3.16
PC (unfilled)	0.189-0.205	1150-1250	Yes	59.1-65.2	1.19-1.21	Weak acid resistivity	3.4-3.64
PC+PET blend (unfilled)	0.18-0.2	1550-1560	Yes	55-60	1.2-1.22	Weak acid resistivity	2.58-2.79
PC+PBT blend (unfilled)	0.18	1500-1570	Yes	47-62	1.2-1.28	Weak acid resistivity	3.4-3.58

TABLE 1: MATERIAL PROPERTIES OF SELECTED POD MATERIALS[4].

[4] Materials are sorted from those with the highest average thermal conductivity (K) at the top to those with the lowest at the bottom. Information in table was collected from the 2017 version of the CES Edu pack (Granta Design Limited, 2017)

EXPLORING PIPE MATERIALS

The second material to consider is the pipe material, which aids the heat transfer between the working fluid and the surrounding medium. Many different materials were considered for the application of the pipe material: metallic alloys, plastics, reinforced materials using glass, carbon, metal, or ceramic fibers, and copolymers. Table 2 below shows the 13 specific materials considered. This table was also sorted by thermal conductivity, with higher thermal conductivities at the top and lower thermal conductivities at the bottom.

Pipe Material	K [W/m-K]	C (J/k-°C)	Strength (MPa)	Density (10^3 kg/m^3)	Durability	Cost (USD/kg)
Copper Alloys	380-400	372-388	30-500	8.93-8.94	Acid, corrosion resistant	6.4-7.1
Aluminum Alloys	76-235	857-990	30-500	2.5-2.9	Acidic deformation	2.21-2.53
ABS (20% carbon)	0.386-0.418	1600-1660	82.4-88	1.13-1.14	Weak acid resistivity	6.94-7.95
ABS (40% aluminum flake)	0.295-0.306	1270-1320	22.8-29	1.54-161	Weak acid resistivity	2.71-2.99
ABS (7% stainless steel)	0.276-0.287	1610-1670	31.5-34.7	1.11-1.13	Weak acid resistivity	3.22-3.66
ABS+PVC (unfilled)	0.264-0.275	1540-1610	29.6-44.8	1.13-1.25	Weak acid resistivity	3.23-3.85
ABS (unfilled)	0.253-0.263	1690-1760	34.5-49.6	1.03-1.06	Weak acid resistivity	2.4-2.84
TPU (Shore D55)	0.24-0.26	1570-1640	14.6-15.4	1.14-1.17	Weak acid resistivity	3.1-4.7
PP (20% mica)	0.245-0.255	1700-1730	31.5-34.5	1.03-1.05	Acid resistivity	1.84-1.92
PVC (unfilled)	0.147-0.293	1360-1440	35.4-52.1	1.3-1.5	Acid resistant	1.4-1.6
PMMA (unfilled)	0.17-0.25	1400-1520	57.8-63.7	1.18-1.2	Weak acid resistivity	2.76-2.87
PP (unfilled)	0.205-0.214	1660-1700	31.9-36.4	0.898-0.908	Acid resistivity	1.45-1.51
ABS (20% glass)	0.193-0.209	1530-1600	57.9-71.7	1.18-1.22	Weak acid resistivity	2.76-3.16

TABLE 2: MATERIAL PROPERTIES OF SELECTED PIPE MATERIALS[5]

[5] Materials are sorted from those with the highest average thermal conductivity (K) at the top to those with the lowest at the bottom. Information in table was collected from the 2017 version of the CES Edu pack (Granta Design Limited, 2017).

Exploring Heat Transfer Fluids

The next aspect of the system to consider is the two types of heat transfer fluids. The system consists of two separate, intertwining pipes within the pod. One pipe carries the working fluid from the house and the second pipe carries water from the well. These two pipes work together as illustrated in Figure 6 for heating and cooling seasons. The working fluid will absorb energy from or expend energy to the surrounding medium through the pipe walls to provide heating or cooling respectively. This fluid will travel through one pipe and up to the residential building where the house can be heated or cooled depending on the season. Options for the working fluid include brines and refrigerants for the transfer of heat, which have been compared side-by-side to water, which is a typical fluid in geothermal heat pump systems. This allows the pod to be a part of the heat pump itself.

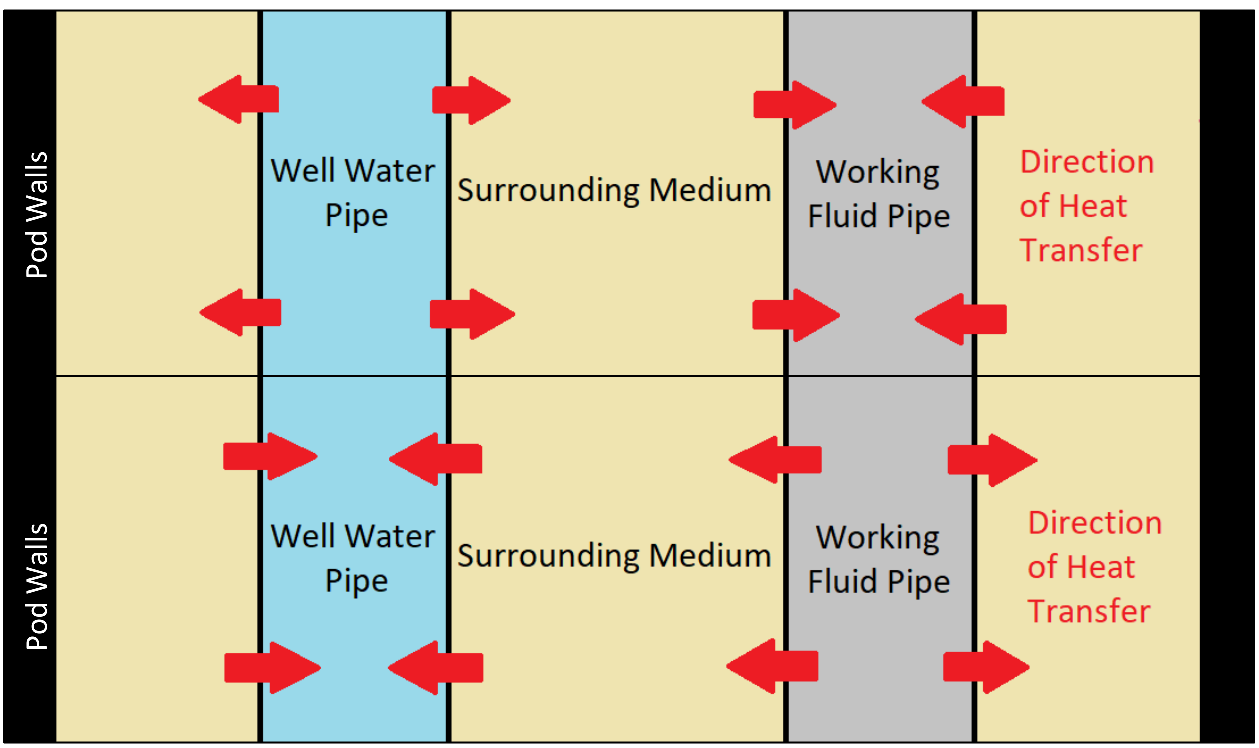


FIGURE 6: HEAT TRANSFER BETWEEN FLUID PIPES AND SURROUNDING MEDIUM FOR HEATING (TOP) AND COOLING (BOTTOM) SEASONS

Well technology was incorporated into the system to utilize the naturally warmer well water to achieve the energy goal for an average residential building. The well water serves as the secondary fluid, which will flow from the well, through the second pipe within the pod, and then be recycled back to the ground where it will eventually be harvested back into the well system after an extended period of thermal contact with the ground. The well water will expend or absorb heat to the surrounding medium for heating and cooling seasons respectively. Below is Table 3 which shows the 6 materials analyzed for the pipe fluid applications. This table was sorted by thermal conductivity at a constant temperature of 10 degrees Celsius, with higher thermal conductivities at the top and lower thermal conductivities at the bottom.

Pipe Fluid	**K at 10°C** (W/m-°C)	**Corrosiveness**	**Flammability**	**Toxicity**	**Cost**
Refrigerant R134a	0.562	Low	Low	Low	High
K_2CO_3	0.543	Low	Low	Moderate	High
Water	0.4715	Low	Low	Low	Low
Glycerol	0.4023	Low	Low	High	High
Methanol	0.204	Low	High	High	Low
Ethyl Alcohol-Water (EA)	0.09202	Low	High	Moderate	Low
Brine/$CaCl_2$ (~30%)	0.01267	Moderate	Low	Low	Low

TABLE 3: PROPERTIES OF SELECTED PIPE FLUIDS[6]

[6] Fluids are sorted based on thermal conductivity(K) with the highest at the top and the lowest at the bottom. Thermal conductivities were collected from the Engineering Equation Solver. Other information from table was collected from The Engineering Toolbox (“Freeze protection of water-based heat transfer fluid”; “Freezing and melting points for common liquids”; “Specific heat of liquids and fluids”; “Thermal conductivities for some common liquids”).

Exploring Surrounding Medium

The surrounding medium in this geothermal heat pump system surrounds the piping configuration within the pod. This material aids the transfer of heat from the well water pipe to the working fluid. Groundwater or brine solutions are typically used in this application for open looped geothermal heat pump systems. However, a thermal storage reservoir is established by implementing a phase change material (PCM). The phase changing material can solidify upon expending energy in the form of heat for heating periods and liquefy upon absorbing excess energy during cooling periods. An infinite cycle of changing phases is formed, providing the necessary heating and cooling for residential applications. Different types of phase-changing material are compared to the conventional material (groundwater) in the qualitative Table 4 shown below.

Surrounding Medium	K	Corrosiveness	Cost	Thermal Cycling
Liquid Metals	Very High	Varies	Moderate	Stable
Hydrated Salts	High	High	Very Low	Unstable over many cycles
$MgCl_2$	High	High	Very Low	Unstable over many cycles
Ground Water	Moderate	Low	Low	Stable
Non-Paraffin Organics	Low	Moderate	Very High	De-compose. at high temps
Refrigerant R134a	Low	Low	High	Stable
Paraffin wax	Very Low	Low	Low	Stable
Methanol	Very Low	Low	Low	Unstable over many cycles
Brine/$CaCl_2$	Very Low	Moderate	Low	Stable

TABLE 4: PROPERTIES OF SELECTED SURROUNDING MEDIUMS[7]

[7] Materials are sorted from highest value of thermal conductivity (K) at the top to the lowest at the bottom. Information from table was collected by Advanced Cooling Technologies ("Phase Changing Material (PCM) Selection").

Phase Changing Materials

The success of geothermal heating systems can often be improved by carefully choosing what kinds of materials are used within the ground portion of the system. For example, choosing the right kind of refrigerants and fluids can make better use of the temperature of the system, while choosing the right pipe material can ensure reliable long-term function of the pipes. Research is currently being done at the United Nations University on using certain phase-changing materials in geothermal systems, which would allow for a higher thermal conductivity (Gupta, 2007).

While water is a PCM, there are other more convenient PCMs, such as paraffin wax. Paraffin's and fatty acids both provide better alternatives as solid-liquid PCMs. PCMs can be used for both energy storage, as well as humidity control, given the proper environment and proper geothermal system (Pielichowska et al., 2014). Figure 7 displays the enthalpy of fusion of the various different classes of phase change materials. The temperature range that most systems are operating at, are highlighted in the peach colored rectangle on the graph below. The higher the enthalpy of fusion, also known as the latent heat of fusion, indicates the change in the energy of the system when a substance changes its state from a solid to a liquid. A release of energy occurs at this time, and the higher the release the better for systems trying to harvest energy. Using a phase change material could be valuable for a geothermal system to aid in load leveling, and for a more efficient method in storing energy.

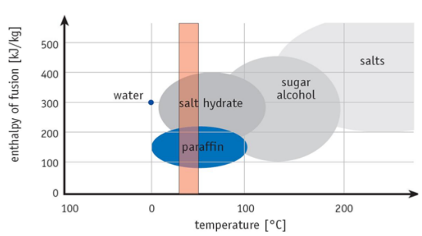


FIGURE 7: PHASE CHANGE MATERIALS FOR THERMAL ENERGY STORAGE

PCMs have four important thermo-physical properties that separate them from each other. These are the melting point, heat of fusion, thermal conductivity and density. These properties are determined using calorimetry. Phase change materials are especially useful because they absorb and release heat at a nearly constant temperature. They store 5-14 times more heat per meter unit volume. There are three classifications of phase changing materials: organic, nonorganic, and eutectic (Sharma, 2009). Eutectics are minimum-melting composition of two or more components, each of which melt and freeze congruently forming a mixture of component crystals during crystallization. A detailed chart illustrating the various properties of phase changing materials can be seen in Appendix A.

Some applications of PCMs include building applications, space-based heat exchangers, thermal storage of solar energy, medical applications, cooling of engines, heating and sanitary hot water, etc. PCMs are used because they enhance the heat transfer in latent heat thermal store. They are utilized in many different forms (Sharma, 2009). Options could be:

- Tank with PCM packed cylinders and heat transfer fluid flows parallel to it
- Tank where pipes containing the fluid are embedded in the PCM
- PCM in spherical containers
- The use of finned tubes with different configurations
- Embed PCM in metal matrix structure; thin aluminum plates filled with PCM
- Graphite-compound-material, where PCM is embedded inside a graphite matrix.

Figure 8 displays a form of phase change material utilization, a cylindrical shell with PCM storage in two different ways[8]. Phase changing material can be used for geothermal applications

[8] Figure 8 was taken from (Sharma, 2009)

because of their ability to store heat. However, PCMs are still not used in geothermal applications because not enough research has been done relating these materials in this industry.

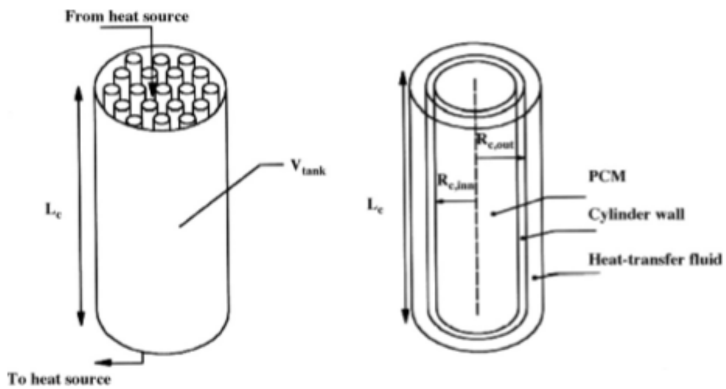


FIGURE 8: CYLINDRICAL SHELL WITH PCM STORAGE

International Ground Source Heat Pump Association (IGSHPA)

The International Ground Source Heat Pump Association (IGSHPA) is a non-profit, member-driven organization established in 1987 to advance ground source heat pump (GSHP) technology on a local, state, national and international level. This association is useful for collecting data having to do with geothermal technology, in order to improve the systems. The association is headquartered on the campus of Oklahoma State University in Stillwater, Oklahoma. According to their website, IGSPHA accomplishes its mission by:

- Advocating for ground source heat pump technology
- Distributing reliable insight and education
- Promoting basic and applied research
- Providing a clearinghouse for relevant information
- Serving as a forum for the development and dissemination of standards

IGSHPA was formed to achieve technical advances in heat pump designs. The most common goal surrounding geothermal heating technology is designing a system that will work for a specific building size given the surrounding environment. The key to designing a highly functional geothermal system is to understand the type of soil at the building site. Different soil types and mixtures will interact with the geothermal system differently since they have different thermal characteristics. Currently, well drillers are needed to install the under pipes of a residential geothermal system due how deep the pipes lay. These companies are required to have an IGSHPA certification before they are allowed to drill and install these systems. IGSHPA certification is given by the IGSHPA which provides training and informational courses for companies who wish to install geothermal technology. The IGSHPA certification teaches well drillers how to evaluate land to see what type of geothermal piping configuration is needed to reach the desired system requirement of the building. The first method for land evaluation is called the ASHRAE Handbook Method which "uses annual average ground temperature, annual temperature amplitude at the ground surface and the phase lag to estimate ground temperatures" (Xing et al., 2017). The second major method for land evaluation is called ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers) District Heating Manual Method which uses a model that estimates the ground temperature by assuming that the average monthly surface ground temperatures are the same as the air (Xing et al., 2017). The above two methods are considered industry standards across the United States for determining the size of the geothermal system needed for a given building.

Geothermal technology has traditionally been used for large industrial buildings. Larger buildings often required deep excavation at the time of building construction of the surrounding earth, allowing for a significantly lower installation cost. Often, industrial buildings will use the ground below large parking lots to place a horizontal piping system. In addition to laying pipes under a parking lot, if the foundation of a building is going multiple stories below surface level, pipes can be placed within the foundation to harvest the geothermal heat directly from the earth. The cost of installing geothermal pipes into the ground can be very expensive; hence installing a system during construction of a building is often the cheapest way to install this technology. Despite a majority of geothermal heating systems being built for industrial usage, the modern market of this technology includes residential homes. However, the small energy usage of a home often poses a difficulty to the geothermal technology functionality which is built for higher loads. The same methods of pipe design and placement are used for residential applications. The result of using the same methods for residential applications is that the installation cost tends to be extremely high and the systems are unreliable. Current technology is not suited for small scale usage which means installing geothermal technology in a residential home has more errors in sizing the system, resulting in poor performance. Thus, this system design has flaws which a new design such as a pod based system has advantages due to its reduced size and ease of installation.

A Model for Ground Temperature Estimations

The Ground Source Heat Pump Association holds a conference every year to discuss developments in geothermal technology. The 2017 conference featured a very important academic article focusing on the methodologies used to evaluate the ground a potential geothermal system would be placed. This article authored by Lu Xing, Jeffrey D. Spitler, Liheng Li, and Pingfang Hu was titled, "A Model for Ground Temperature Estimations and Its Impact on Horizontal Ground Heat Exchanger Design" (Xing et al., 2017). This article proposed a new method of soil and ground evaluation that future installers of this technology could use to increase the reliability of their system performance. This article used The Soil Climate Analysis Network (SCAN) report which collects the ground temperature of 12 sites across the US at 4 different depths of the earth. Using this measurement data as reference in this paper, the authors calculated the optimal pipe length for a theoretical system at each of the 12 predetermined locations. To compare the optimal pipe length, the authors then used the two standard methods, ASHRAE Handbook Method and the ASHRAE District Heating Manual Method, to determine the theoretical pipe length needed for a geothermal system at each of the 12 SCAN report location. The final part of the article was to explain the author's new Evaluation method for theoretically estimating the pipe length of a system which they called the Xing and Spitler Model. This model is a mathematical estimation tool to predict ground temperatures using, "five weather-related constants -annual average undisturbed ground temperature, two annual amplitudes of surface temperature variations and two-phase angles" (Xing et al., 2017). The results of comparing the new Xing and Spitler Model with the old handbooks concluded that all three methods had significant percentage of error in prediction the needed pipe length of the geothermal system of the area (See Figure 9).

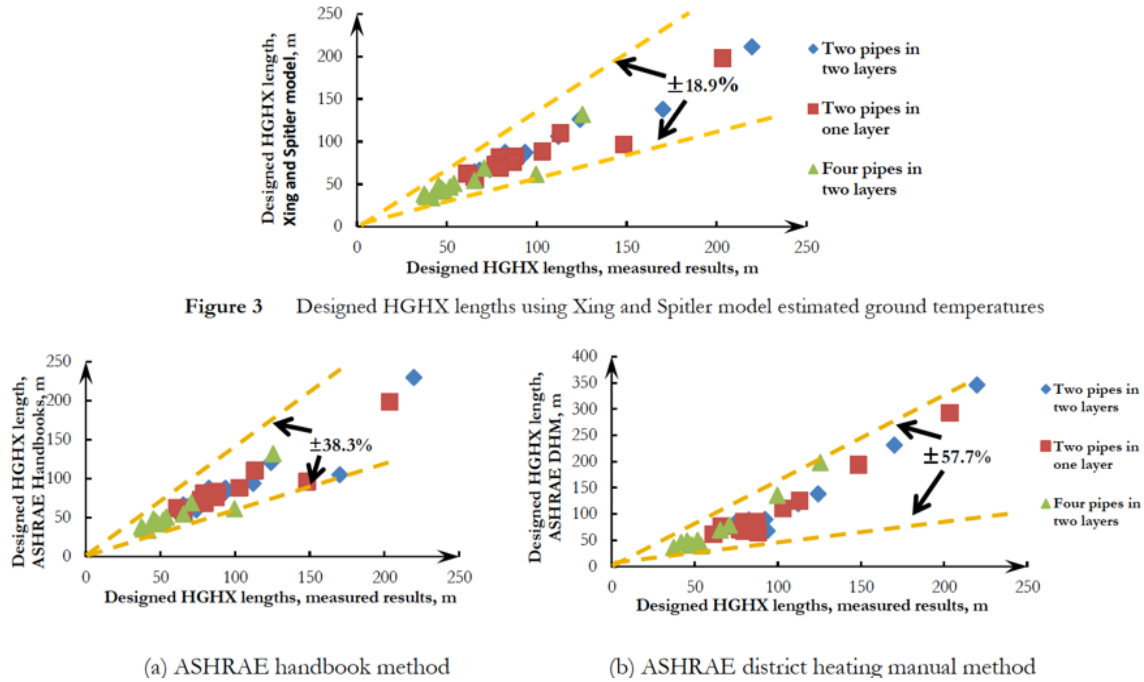


FIGURE 9: A MODEL FOR GROUND TEMPERATURE ESTIMATIONS AND ITS IMPACT ON HORIZONTAL GROUND HEAT EXCHANGER DESIGN[9]

The original two ASHRAE methods have 38.3% and 57.7% error in accurately predicting the pipe length needed for a geothermal system, while the new Xing and Spitler Model has an 18.9% error. The Xing and Spitler Model has significantly less percent error, it is very important to notice that these predictions are not reliable due to the high error percentage, which means there is still a great risk in designing geothermal systems. Without actually confirming ground temperatures of local soil, there is no guarantee that any geothermal system will function at its highest potential. Thus, a need for a system design, such as a pod, will help create the way for more reliable geothermal systems in the future.

[9] Figure taken from "A model for Ground Temperature Estimations and Its Impact on Horizontal Ground Heat Exchanger Design" (Xing et al., 2017).

The Future of Geothermal Technology

Geothermal technology has many benefits and an alternative to traditional fuel source since it uses high efficiency technology compatible with other renewable resources. However, there are many drawbacks which have kept the technology from advancing within the modern energy industry in the United Sates. Size and cost are two of the major drawbacks that create issues for those wishing to install these systems. The size of the system is a concern because the current systems can often include hundreds of feet of buried piping. This is directly related to the system cost which includes the cost of installing the pipes underground which can be expensive. While there is a large market for effective renewable energy technology, the northeast does not appear to be the ideal location for geothermal systems due to the colder climate and lack of hotspots.

Geothermal energy is still a relatively new for renewable energy technology on the global market. Currently, Iceland is the leader of the geothermal energy market making significant strides in advancing this technology. However, Iceland primary uses geothermal technology for large scale power plants. At this time the cost and the amount of space that geothermal systems take up are still some of the biggest limiting factors of using geothermal energy in single home residential buildings. Advancements are currently being made to decrease the size of the system so that the outdoor components of the geothermal system are both less expensive and take up less space. As this technology continues to improve the cost and size which continue improve which could lead to an increase in awareness of this technology as the use of traditional fuel sources become obsolete.

METHODOLOGY

The goal of this project is to build a model to capture the thermal performance of a modular geothermal heating system. This system will be constructed based on basic energy and water conservation principles. The legality of returning ground water back into the Earth's natural reservoirs was considered and deemed not an environmental concern in the United States ("Environmental Impacts of Geothermal Energy", n.d.). In order to complete this goal, the understanding of how current geothermal systems work and why they are not more commonly used in residential homes in United States was assessed. For modeling this system, a modular geothermal heat pump was mathematically modeled using Engineering Equation Solver, an iterative mathematical solver developed at the University of Wisconsin-Madison. In our model, several inputs were required (which as listed in Table 5) to generate the output energy to compare to the system requirements of 3,242.7 Watts for one heating system, which will be delved into later on in the discussion. Due to the complexity of the project and the time frame allowed, details such as corrosion were not taken into full consideration during the fabrication of the model. Corrosion was briefly looked at during the material selection phase. In order to complete this project successfully, the following objectives were developed:

1. Improved the mathematical model of the geothermal heat pump to account for the ground elements.
2. Designed a new heat exchanger unit.

The previous MQP, *Modular Geothermal Heat Pumps*, focused on developing the EES code framework for calculating the heat transfer within the pod. The key objective of this project focused on the expansion of the code and inclusion of the effects of the ground on the heat transferred within the system. Once the mathematical model was completed, many different variables were iterated which could be altered in the development of the pod in order to develop an optimized design of a new heat exchanger system and to identify the aspects most important to the design.

Improvement of EES Model

The analysis technique of this project was to continue the development of the EES code that was initially started by the 2017 MQP group. In 2017, this group created a code using EES software to model a geothermal system. Although this code was a great framework for the project, the group did not focus on the heat transferred from the ground. This project goal is to improve the 2017 code to include the effects of the ground. Additionally, the code was changed so that a residential well could be included in the system. To do this, the following design objectives were developed to improve the EES code. These objectives include: increased performance, increased manufacturability, reduced cost, and decreased size of the system. In addition, two objectives were created to check the final system: ensured energy required of the home matches the energy output of the optimized unit and ensured that the water required of the well is sustainable. The final version of the EES code was simplified to allow future teams to fully understand the code and how it works.

Design of the Pod

The following section describes the process used to develop a suitable heat exchanger configuration to be used in the United States that satisfy the following design requirements:

Design Objectives:

1. Increased the performance of the pod.
2. Enhanced the manufacturability of the system.

3. Reduced the cost of the system.
4. Decreased the size of the system.
5. Ensured that the energy required of the home matches the energy output of the optimized unit.
6. Ensured that the water required of the well is sustainable.

Design Objective 1: Increased the Performance of the Pod

Within the ESS model different variables were iterated from the base system including the pod size and the materials used throughout the system. Using standard data analysis techniques, recommendations were determined for the most appropriate system configuration.

Base System

The optimal geothermal modular system has the parameters which increased the performance of the system at the reduced size were used. In order to determine these parameters, a base system was built, and then the various material and physical parameters were iterated one at a time for find the optimal design.

For calculation purposes, a spherical model of the ground was used with a one-meter radius dimension. The properties of the ground were based off of the material Sandy Clay with a thermal conductivity is equal to 1.7 W/m-K, and the pod material was chosen to be aluminum. Based off of research, it was decided that the base system would consist of standard aluminum pipes. It was also decided that methanol would be used as the base working fluid and $CaCl_2$ for the base surrounding medium in the pod. In addition, the length of the pod pipe was initially 25 m, the depth of the well was 25 m, the temperature of the ground and pod was 10°C and 7.2°C respectively, the diameter of the pod and well pipes were 0.0229 m, the heat transfer coefficient was 1598 W/m^2-K, and the temperature of the pod pipes and the well were 7°C and 1°C respectively. For functional purposes, a majority of baseline system material choices were chosen due to recommendations from the previous *MQP* 2017. The assumptions and research lead to the parameters outlined in Table 5 and an energy output of 755 Watts.

Variable	Value	Unit
Ground Shape	Sphere (R=1m)	-
Ground Material	Sandy Clay	-
Pod Material	Aluminum	-
Pipe Material	Aluminum	-
Working Fluid	Methanol	-
Surrounding Medium	$CaCl_2$	-
Length of Pod Pipe	25	m
Length of Well Pipe	25	m
Temperature of the Ground	10	°C
Outer Diameter of Pipes	0.0254	m
Inner Diameter of Pipes	0.0229	m
Heat Transfer Coefficient (H) of Water Inside Well Pipes (Based on Correlations)	1598	W/m^2-K
Temperature of the Pod Pipes	7	°C
Temperature of the Well	1	°C
Pod Thickness	0.1	m
Mass Flow Rate	10	m/s
Overall Energy Output	755	W

TABLE 5: IMPORTANT NUMERICAL VALUES FOR BASELINE SYSTEM

GROUND MATERIAL

Due to the inclusion of the ground into the EES code, it was important to consider the type of ground material that would be utilized within the design. There are many aspects of the ground that will affect the transfer of heat to the geothermal system; some of these include the thermal conductivity, the water content, the density, and the specific heat. In order to build a system that can work in diverse locations, under diverse ground conditions, different types of ground were iterated within the code. The ground types can be found in Appendix B.

Pod Pipes

The pod pipes include the configuration of pipes that create a cycle for the working fluid to travel up to the house and back down to the pod. The length of these pipes and the value of the heat transfer coefficient for forced convection within these pipes are two important parameters to consider for the system. Similarly, the flow rate of the working fluid within the pod pipes also affects the overall energy output of the system. These variables will affect the time period and rate at which heat transfer can occur within these pipes. Consequently, these three variables will be iterated in the EES code to determine their significance and choose optimized values for the final design.

Well Water Temperature

Characteristic residential water wells harvest the groundwater from underground aquifers. In different locations on the Earth, groundwater can be different temperatures. In the United States alone, groundwater can range from 44°F (6.67°C) in the northern regions to 80°F (26.67°C) in southern regions like Florida or Texas (“What is the temperature of the available groundwater?”, n.d.). In order to encompass varying temperatures, well water temperature was iterated in the EES code to explain sensitivity and identify if a likely limit exists.

Size of Pod

The EES code models the pod of the system as a sphere with only two defining dimensions: pod thickness and pod radius. These two parameters contribute to the overall size of the pod, which affects how much pod material was used, how much surrounding medium the pod can contain, and how long of piping in the pod the system can have. In order to test how the pod size affects the overall energy output of the system, both pod thickness and pod radius were changed and iterated within the code.

MATERIALS

The next step to designing a geothermal system was to decide upon the materials that will be used throughout the model. Pod and pipe material, working fluid, and surrounding medium all have different criteria that helped determine which choices optimized the system's performance and efficiency.

POD MATERIAL

Two important parameters considered in the selection of the pod material were thermal conductivity (K) and the specific heat capacity (C). Thermal conductivity of the material's capacity to transport heat (González-Viñas, 2003). For the pod material, it was important for the material to have a high value of thermal conductivity so that heat can be quickly transported from the ambient environment to the surrounding fluid through the pod walls. Specific heat capacity, which was also considered, is the amount of energy that is required to increase the material's temperature by 1 degree (González-Viñas, 2003). Other factors that affect the material selection were the process ability, strength, durability, density, and cost. The material needed to be easily processed based on the design shape. It also must have been both strong and durable to support longevity of the system under the corrosive medium of the ambient environment and surrounding medium. In addition, the material needed to be able to withstand the natural movement of the earth without cracking or deforming. A pod material was more desirable if the density of the material was low for installation and maintenance purposes, as well as economically feasible.

In Table 1, the properties of the pod materials are recorded. Some materials such as stainless steel, copper alloys, ABS (20% carbon filled), and PC (20% carbon filled) were deemed undesirable due to their steep costs. Although these materials have other redeemable qualities, such as copper's high value of conductivity and stainless steel's high value of strength, the cost of these materials made them economically irresponsible choices. All other materials had reasonable costs and desirable ranges of conductivity, specific heat, strength, density, and durability. For comparison purposes, all 21 materials were used in the iterations for the mathematical geothermal model in order to determine which material was the best.

Pipe Material

To reach the ideal heat transfer conditions of the system, the pipe material must have a high thermal conductivity. With a high conductivity, heat could quickly pass from the surrounding fluid to the working fluid through the pipe walls. Specific heat capacity was another important material property to consider in the choice of pipe material. Materials with low specific heat require less heat to change temperature compared to materials with higher specific heat capacity. In addition, it was important that the material was relatively strong and durable to prevent pipe cracking and deterioration under working conditions. Working conditions includes both high and low temperatures, a corrosive environment provided by the surrounding medium, and pressure due to the volumetric flow rate. Nonetheless, the pipe material needed to be lightweight for ease of installation and low in cost.

Using the criteria mentioned, some pipe materials from the table in Table 2 could be identified as poor choices. However, the 2017 *Modular Geothermal Heat Pumps* MQP proved that the slight variations in thermal conductivity for the pipe materials showed very little impact on the overall heat transfer within the system. Therefore, this variable was chosen to not be varied, and instead use aluminum as a constant in the iterations because it is readily available for pipes, which in the end the material doesn't matter anyway.

WORKING FLUID

In order for the working fluid to be able to easily heat or cool within the pod, the material must have low specific heat capacity, high thermal conductivity, and function as a fluid within the working temperatures of the ambient environment—around 50°C. In addition, it is best for the material not to be corrosive, flammable, or toxic. These characteristics with ensure that the pipes do no degrade over time; and if this fluid somehow leaks into the pod or into the ambient environment then there will be less of an environmental concern. Like any other material used in this design, the working fluid should also be inexpensive to maintain economic feasibility.

The material choices in Table 3 were used in the iterations for the mathematical geothermal system in order to identify which working fluid would be most efficient. Although toxic, the recommendation from *Modular Geothermal Heat Pumps* states using methanol as the ideal working fluid. Methanol is a common fluid used in geothermal applications that can be used in the desired temperature ranges. According to this project, methanol is also low in cost and corrosively. In order to confirm the validity of the recommendation, the mathematical model was iterated with all the fluids in Table 3.

SURROUNDING MEDIUM

For phase changing materials, heat of fusion should be high, thermal conductivity low, and the phase change should occur within the working temperature range of the system. In addition, the material should not be toxic or dangerous in case of leakage into the ambient environment and to prevent degradation of pod and pipe material. As always, the surrounding medium should be low in cost and should produce little resistance to heat transfer between the well/ground and heat pump circuits.

If storage was needed, as referenced in Table 4, the PCM that was chosen worked in the range of temperature that was needed that also had low costs and a stable thermal cycling within the working temperature range: paraffin wax. This particular PCM comes in many different varieties. Paraffin wax with 15 carbon atoms was chosen because the melting point is 10 degrees Celsius and the latent heat of fusion is relatively high (Pielichowska, et al., 2014)

Phase changing materials are especially useful in geothermal applications for their ability to form an infinite cycle where the material can absorb heat when needed during cooling seasons or expend heat when needed during heating seasons. In order for to see if paraffin wax with 15 carbon atoms would work in the system, the amount of PCM was calculated which would be needed to be able to provide enough energy for an average residential home throughout the year. If the average house uses between 15,000 to 20,000 BTU/hr while undergoing a heating season of 6 months (Pielichowska, et al., 2014)). Using an average density of paraffin waxes of 900 kg/m^3, the volume was determined of this PCM that would be required. For 15,000 and 20,000 BTU/hr, 371 or 494 m^3 of the PCM would be needed respectively. This translates to a cube of length 124 or 165 m respectively. This is much too large of a size for the pod. At best, PCM could be used as a short term storage to level the heating load as this study concentrates on steady state performance, PCM will not be considered in the future. Therefore, PCM would not be utilized in the mathematical model. Instead, other surrounding mediums in Table 4 were tested in the mathematical iterations.

Design Objective 2: Enhanced the Manufacturability of the System

The major design objective of the project was to make the geothermal system modular, so it could be made as a unit in a factory and shipped to residential homes. The main reason for this objective is to allow for ease of installation and maintenance of the system.

Designing a modular system will open up many doors for the product in a manufacturing sense. If the system is able to be transported in a standard 18-wheel truck and trailer, the ability to manufacture it as a unit to be installed in a very standard way will increase the appeal of this new design. The shape of the pod is very important as well; cylindrical and spherical pods require a lot of machining, which can be expensive. This limits material choices as well as because not all materials can be shaped easily.

Design Objective 3: Reduced the Cost of the System

A major source of cost in the traditional geothermal is the low rate of the heat transfer from the ground to the House. Increasing the effectiveness of the system and decrease the size of the system is a large part of reducing the cost of the system. The two most significant factors to reducing the size of the system were the length of the piping and the size of the pod. By doing this, fewer raw materials would be needed to accommodate the energy needs of the residential building, thus reducing the overall cost of the system. Furthermore, material selection also affects the cost of the geothermal systems. Utilizing materials like plastics for the pipes and pod would be cheaper than using metals and fiber-reinforced materials. However, these materials are typically less thermally conductive, which likely would affect the efficiency and performance of the system. Therefore, in order to minimize the cost of the geothermal system, there needed to be a balance between reducing the size and choosing proper materials to increase the efficiency of the system.

Design Objective 4: Decreased the Size of the System

In modern geothermal systems, a limiting factor of the effectiveness of the system is the size of the ground pipes in the system. For this objective, the average New England household energy usage was researched and evaluated to determine a model value of 11,000 Btu/HR for the average energy usage of a home. This was calculated using research from the group's average home oil usage and conversions online. Once the energy usage value was given in the EES model, the volume of the ideal pod could be found.

One of the solutions to reduce the volume of pipes needed in the ground was to create an open loop geothermal system attached to the pod. With an open loop system, the piping would only need to go down into a ground water source, and back up to the heat exchanger unit using a traditional residential well configuration. The water source could then be used to bring a fluid into the heat exchanger, to where the working fluid can be heated up, and distributed to the residential home. The addition of an external source of heat could in turn reduce the size of the system needed to function optimally in the New England Area.

Design Objective 5: Ensured that the Energy Required of the Home Matches the Energy Output of the Optimized Unit

After completing all of the design objectives, the system specifications were selected based on how they maximized the energy output, reduced the cost, and optimized the overall performance and efficiency of the system. These system specifications made up the optimized pod design, which was returned into the EES code to achieve the optimal energy results.

According to the U.S. Energy Information Administration, approximately 5.7 million home use heating oil as their source of fuel. In 2017, the United States used 3.1 billion gallons of heating oil ("Heating Oil Explained", 2018). This means that an average home uses approximately 544 gallons/year. In order to be conservative with this number, it was approximated that the typical home in the United States used 700 gallons/year for a medium sized home. Each gallon of heating oil produces 138,500 BTU ("Energy Units and Calculators Explained", 2017). This means that 700 gallons/year correlates to energy of 11,067.35 BTU/hr or

3,242.7 Watts for continuous heating over a cold season. This quantity was compared to the output of energy for the optimized pod design in the results section. One unit of the modular system must either be able to support this energy need alone, or be able to be combined as many units to together support the energy requirement in the United States.

Design Objective 6: Ensured that the Water Required of the Well is Sustainable

Once the system passed the energy check, it was determined that a typical water well could support the demand of the system. In order to do this, the amount of water the system needed, based on the energy demand of the house, was determined. This amount of water must be able to be pumped by typical water well for residential buildings. These two final checks ensured that the system is practical for residential use in the United States.

RESULTS

The following section is a complete summary of the EES Code and results of the iterations as described in the project methodology.

IMPROVEMENTS OF EES MODEL

The following section explains in detail the additions that were made to the 2017 MQP code to include the effects of a well and the ground. In order to simplify and organize the EES code, it was split up into sections: well resistance equations, ground resistance equations, pod resistance equations, and total energy output.

CODE OVERVIEW

For the EES model of the system, it was established that the heat added to the system, or the Q value, is the most important factor in determining the efficiency of the system. The code included general Q equations for determining the energy needed from the ground to the working fluid of the system. The code was split into three primary parts, with the first part being the given values of the temperature from the house into the pod, and then the ideal temperature from the working fluid into the pod. The second part of the code establishes the resistance equations for the transfer of energy into the well, the ground, and the pod. Finally, the third part of the code uses the Q value for each of the components and totals them together to get the final Q output of the entire system. A complete copy of the EES code is located in Appendix C. The first figure below visually explains each resistance and how it is connected within the model. The well and ground resistances are shown in a parallel configuration to represent that the heat input into the model from each of these sources are independent.

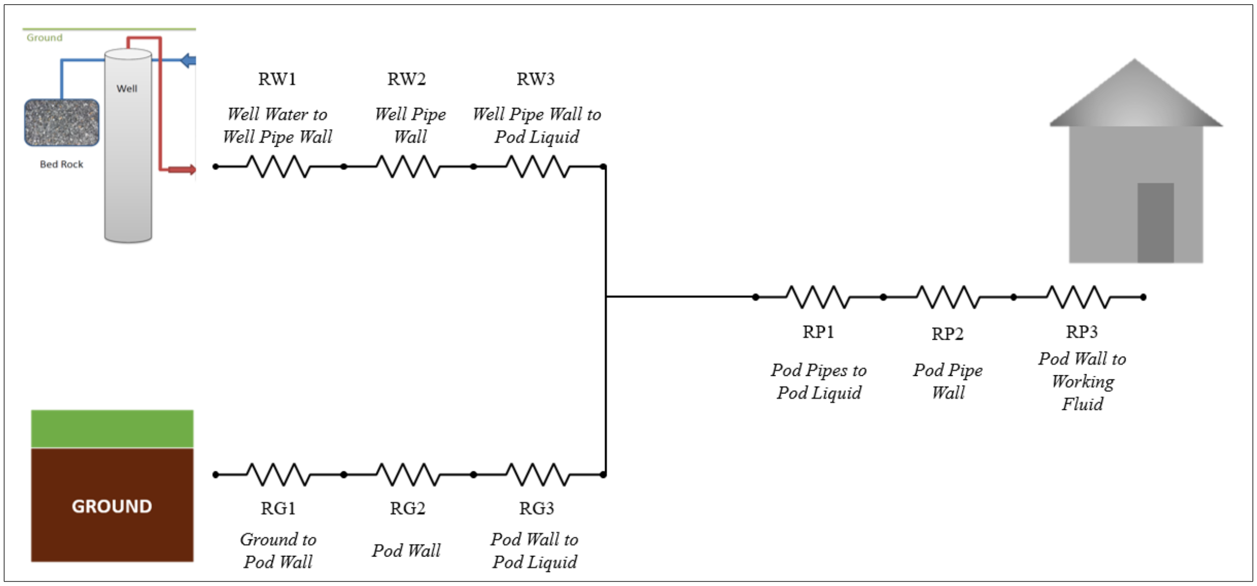


FIGURE 10: RESISTANCE DIAGRAM FOR EES CODE

The EES Block Diagram below visually shows the method for which a variety of inputs were included in this model to achieve the final solution of solving for the temperature of the working fluid of the Pod Pipe back into the House. In addition to inputs, the general calculations are also included to help further overview the model.

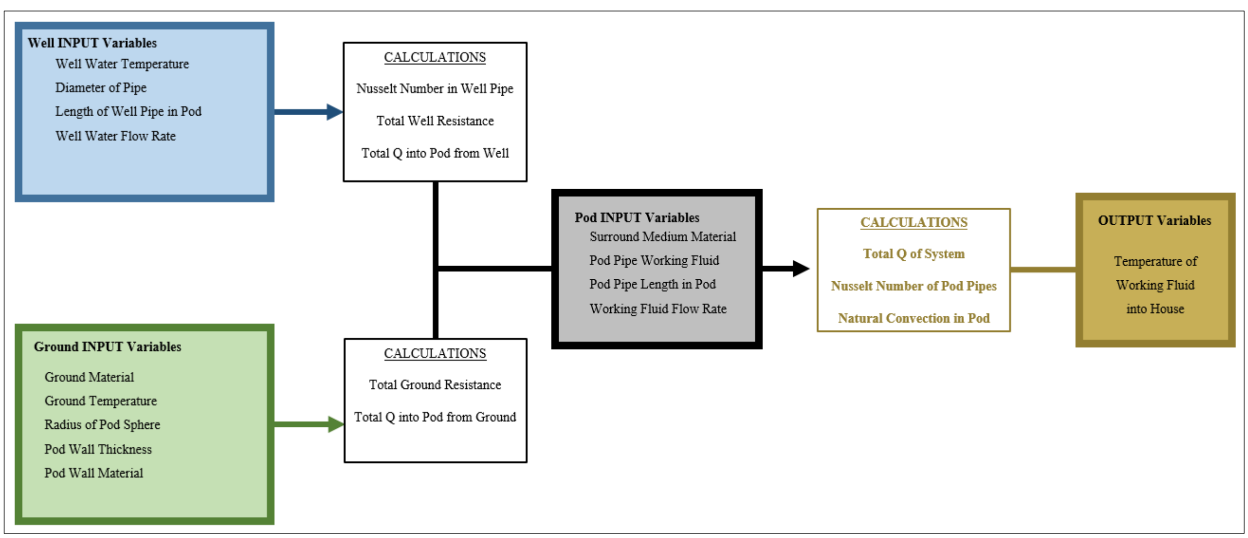


FIGURE 11: EES CODE BLOCK DIAGRAM

WELL BRANCH RESISTANCE EQUATIONS

The second part of the code used the information from the first part of the code, and established thermal resistance values from the well, and through the ground and the pod. To begin to determine the thermal resistance value of the well, the code was provided with several inputs. For the inputs of the well, the following was determined: the temperature of the well water to be 12.7° Celsius, the pressure of the well to be 344 kPa (or 50 psi), the temperature of the pod liquid to be 7.2° Celsius, the pressure of the pod to be 262 kPa, the outer diameter of the well to be 0.025 meters, the inner diameter of the well to be 0.0229 meters, the length of the piping of the well to be 25 meters, gravity to be 9.81 m/s^2, the thermal conductivity of aluminum to be 205 W/m*K, the thermal conductivity of water, and finally the Nusselt number for inside of the well pipe to be 3.36 which means the flow is laminar.

RW1 was labeled to be the well water resistance. The thermal conductivity of water and the Nusselt number of the well pipe were multiplied and divided by the inner diameter of the pipe to determine the convection coefficient. With this convection coefficient, it was used in the equation 1/H*A to determine the thermal resistance of the well water, where "A" is the surface area of the pipe and "H" is the convection coefficient. The "H" value was found using the mass flow rate of the well water. This "H" value calculated using standard correlations and the calculations from Appendix F.

RW2 was labeled to be the well pipe wall resistance. To determine the well pipe wall resistance, the equation for conduction through a cylindrical wall was used. For this equation, the natural log of the inner diameter of the pipe over the outer diameter of the pipe was used, which was put over the thermal conductivity of the well material, multiplied by 2 * pi * the length of the well pipe.

RW3 was labeled to be the natural convection resistance between the pipe and the brine. To determine this resistance, the Rayleigh number was calculated using the alpha, beta, and nu values. The Rayleigh number equation, and the Prandtl number was calculated for free convection, in order to calculate the Nusselt number for the outside of the well pipe. With this value, the free convection coefficient was able to be solved. Lastly, both the natural convection coefficient, and the area of a cylindrical pipe were used in the equation 1/H*A to determine the resistance between the pipe and the brine in the well. These are shown in Figure 12 below.

RW1 Well Water Resistance

hW1 = (Nuss$_{inwellpipe}$ * Kwater)/Di$_{wellpipe}$

$$hW1 = Excel_h \cdot \frac{6}{100}$$

$$RW1 = \frac{1}{hW1 \cdot 2 \cdot \pi \cdot Di_{wellpipe} \cdot L_{well}}$$

RW2: Well Pipe Wall Resistance

$$RW2 = \frac{\ln\left[\frac{Di_{wellpipe}}{Do_{wellpipe}}\right]}{2 \cdot \pi \cdot L_{well} \cdot Podwall_{mat}}$$

RW3 Pipe to Brine Resistance -Natural Convection

Caluclate Ra using beta and nu and alpha pg 492

$$Ray_{W3} = \frac{g \cdot \beta_{br} \cdot (Tpodliquid - Tpodpipe) \cdot Do_{wellpipe}^{3}}{\nu_{br} \cdot \alpha_{br}}$$

Prandtl Number Equation from Wiki

$$Pr_{W3} = \frac{\nu_{br}}{\alpha_{br}}$$

pg502 use brine properties to define Ra and Pr

$$Nuss_{outsidewellpipe} = \left[0.6 + \frac{0.387 \cdot Ray_{W3}^{(1/6)}}{\left[1 + \left[\frac{0.559}{Pr_{W3}}\right]^{\left[\frac{9}{16}\right]}\right]^{\left[\frac{8}{27}\right]}}\right]^{2}$$

area is entire surface are of the pipe based on pipe length and diameter

$$AW3 = \pi \cdot L_{well} \cdot Do_{wellpipe}$$

$$hW3 = \frac{Nuss_{outsidewellpipe} \cdot Pod_{fluid}}{Do_{wellpipe}}$$

$$RW3 = \frac{1}{hW3 \cdot AW3}$$

FIGURE 12: WELL RESISTANCES PART 1

GROUND RESISTANCE EQUATIONS

Next, the thermal resistance of the ground was determined. The beginning portion of the code with the inputs for the ground being: the temperature of the ground at 10° Celsius, the temperature of the brine to be 7.2° Celsius, the thermal conductivity of the ground to be 1.7, the radius of the outer sphere of the ground model to be 3 meters, the distance from the inner pod wall to the pipes to be 1 meter, the area of the pod liquid to be 1 meter squared, the convection coefficient for a vertical plate with natural convection to be 35 (units), and the convection coefficient of a horizontal plate with natural convection to be 41 (units). The thermal conductivity of the ground was determined with the assumption that the ground was uniform clay/silt in a 1-meter radius sphere.

RG1 was labeled as the information for the ground, modeled as a sphere. A shape factor was used to calculate Qground as if the sphere was buried in a semi-infinite medium. The following Figure shows how the pod was a "z" depth underground with a diameter "D". The temperature of the pod is represented by "T1" and the temperature of the surface air was "T2". The final Shape Factor "S" was then used in place of the traditional heat transfer equations (Q = kS[T1 – T2]) (Bergman & Incropera, 2011).

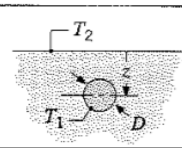
System	Schematic	Restrictions	Shape Factor
Case 1 Isothermal sphere buried in a semi-infinite medium		$z > D/2$	$\frac{2\pi D}{1 - D/4z}$

FIGURE 13: SHAPE FACTOR EQUATION (BERGMAN & INCROPERA, 2011)

RG2 represents the resistance of the pod wall. The thermal resistance of the sphere of the pod was calculated using conduction. At this point, the volumetric shape factor was determined in this portion of the code using a spherical model.

RG3 was labeled as the information of the pod liquid. The coefficient of convection was determined by taking the average of the convection coefficient for a vertical plate with natural convection, and the convection coefficient of a horizontal plate with natural convection. Then, by using this value, and the surface area of the pod, the thermal resistance could be calculated. These equations are all shown below in Figure 14.

RG1 Ground Info : Modeled as Sphere

$rs2 = rs1 - Ground_{thickness}$ Inner radius of the ground sphere in model aka the size of the POD, and ground-thickness changes

$$RG1 = \frac{rs1 - rs2}{4 \cdot \pi \cdot rs1 \cdot rs2 \cdot Kground}$$

RG2: Pod Wall Info (Modeled as a Sphere)

add Shape Factor

$rp2 = rs2 - Pod_{thickness}$ radius of inner pod (.01 thickness) and old rp1= current rs2)

$$RG2_{sphere} = \frac{rs2 - rp2}{4 \cdot \pi \cdot rs2 \cdot rp2 \cdot pod_{material}}$$ Sphere

-------------------shape factor-----------------

$D = rs2 \cdot 2$

$z = rs1 + 1$ [m] rs1 is input

$$S = \frac{2 \cdot \pi \cdot D}{1 + 0.25 \cdot \frac{D}{z}}$$

Qpodwall = S*kal*(Tg1 - Tg2) is the shape factor equation which means --> [R = 1/SK]

$$RG2_{sfactor} = \frac{1}{S \cdot pod_{material}}$$

RG3: Pod Liquid Info

$$hG3avg = \frac{hG3v + hG3h}{2}$$

$h_{forced} = 200$ [W/m^2*K]

$$RG3 = \frac{1}{hG3avg \cdot AG3}$$

FIGURE 14: GROUND RESISTANCES PART 2

POD RESISTANCES EQUATIONS

Next, the thermal resistance of the pod was determined. This portion of the code began with the inputs for the pod being: the temperature of the pod liquid at a value of 7.2° Celsius, the temperature of the working fluid 6° Celsius, the outer diameter of the pipe inside the pod being 0.025 meters, the inner diameter of the pipe inside the pod being 0.0229 meters, and the length of the pipe inside the pod being 25 meters.

RP1 was labeled as the thermal resistance between the pipes in the house, and the brine. This thermal resistance value was determined by calculating Rayleigh's number using the alpha, beta, and nu values. The Rayleigh's number equation and the Prandtl number were calculated for free convection, in order to calculate the Nusselt number for the outside of the well pipe. With this value, the free convection coefficient could be solved. Lastly, the natural convection coefficient, and the area of a cylindrical pipe would be used with the equation 1/H*A to determine the resistance between the pipe and the brine in the pod.

RP2 was labeled as the thermal resistance of the pipe wall. To determine the well pipe wall resistance, the equation for conduction through a cylindrical wall was used. For this equation, the natural log of the inner diameter of the pipe over the outer diameter of the pipe was used calculated and put over the thermal conductivity of the pod material pipe multiplied by 2 * pi * the length of the pipe in the pod.

RP3 was labeled as the thermal resistance of the pipe working fluid. The Nusselt number from the pipe inside the pod was used to calculate the convection coefficient. Lastly, the area of the pipe inside the pod was used, and the convection coefficient to solve for the thermal resistance.

The third and final part of the code takes the resistances from the ground, the well, and the pod, and allows for the Q values of each component to be determined. When all of the Q values from all the components are added, the total Q value for the heat input into the house can be determined. For the Q value of the ground, the values RG1, RG2, and RG3 were used for the resistance values. By taking the temperature of the pod liquid, and subtracting it by the temperature of the ground, and then putting it over RG1 + RG2 + RG3, the Q value of the ground component can be determined. The summation can be seen in Figure 15.

RP1 House Pipes to Brine Resistance - Natural Convection

Caluclate Ra using beta and nu and alpha pg 492

$$Ray_{P1} = \frac{g \cdot \beta_{br} \cdot (Tpodliquid - Tpodpipe) \cdot Do_{podpipe}^{3}}{\nu_{br} \cdot \alpha_{br}}$$

Prandlts Number

$$Pr_{P1} = \frac{\nu_{br}}{\alpha_{br}}$$

pg502 use brine properties to define Ra and Pr

$$Nuss_{outsidepodpipe} = \left[0.6 + \frac{0.387 \cdot Ray_{P1}^{(1/6)}}{\left[1 + \left[\frac{0.559}{Pr_{P1}}\right]^{\left[\frac{9}{16}\right]}\right]^{\left[\frac{8}{27}\right]}}\right]^{2}$$

area is entire surface are of the pipe

$$AP1 = L_{podpipe} \cdot \pi \cdot Do_{podpipe}$$

$$hP1 = \frac{Nuss_{outsidepodpipe} \cdot Pod_{fluid}}{Do_{podpipe}}$$

$$R_{P1} = \frac{1}{hP1 \cdot AP1}$$

RP2: Pipe Wall Resistance

$$R_{P2} = \frac{\ln\left[\frac{Di_{podpipe}}{Do_{podpipe}}\right]}{2 \cdot \pi \cdot PodPipe_{mat} \cdot L_{podpipe}}$$

RP3: Pipe Working Fluid Resistance

$$Nuss_{inpodpipe} = 3.36$$

$$hP3 = \frac{Nuss_{inpodpipe} \cdot WorkingFluid}{Di_{podpipe}}$$

$$R_{P3} = \frac{1}{hP3 \cdot 2 \cdot \pi \cdot Di_{podpipe} \cdot L_{podpipe}}$$

FIGURE 15: POD RESISTANCES PART 3

Total Energy

For the Q value of the well, the values RW1, RW2, and RW3 were used for the resistance values. By taking the temperature of the pod liquid and subtracting it by the temperature of the well water, and then putting it over RW1 + RW2 + RW3, the Q of the well component can be calculated.

Finally, for the Q value of the pod, the values RP1, RP2, and RP3 for the resistance values. By taking the temperature of the working fluid and subtracting it by the temperature of the pod liquid, and then dividing it over RP1 + RP2 + RP3, the Q of the pod component could be determined. By adding the values of the Q values of these components, the total Q of the entire system was found. This is shown in Figure 16. Once the final Q was found, a final temperature check was run to ensure the previously calculated Q values were within range of realistic values (Figure 17). For example, if the Q values computed with the main EES code showed the final temperature of the water flowing back into the house to be a temperature below freezing, the would show the model wasn't working.

PART3: Final Q output for System

Q_{ground}

Temps: 50F to 45F

Temp-in = Tground

Temp-out = Tpodliquid

R-values: RG1, RG2, RG3

$$Q_{ground} = \frac{Tground - Tpodliquid}{RG1 + RG2_{sfactor} + RG3}$$

Q_{well}

Temps: 55F to 45F

Temp-in = Twellwater

Temp-out = Tpodliquid

R-values: RW1, RW2, RW3

$$Q_{wellR} = RW1 + RW2 + RW3$$

$$Q_{well} = \frac{Twellwater - Tpodliquid}{RW1 + RW2 + RW3}$$

Q_{pod}

Temps: 45F to 40F

Temp-in = Tpodliquid

Temp-out = Tworkingfluid

R - values: RP1, RP2, RP3

$$Q_{pod} = \frac{Tpodliquid - Tworkingfluid}{R_{P1} + R_{P2} + R_{P3}}$$

Total Q:

$$Q_{total} = Q_{ground} + Q_{well} + Q_{pod}$$

$$R_{total} = RG1 + RG2_{sfactor} + RG3 + RW1 + RW2 + RW3 + R_{P1} + R_{P2} + R_{P3}$$

$$UnitArea = 1 \quad [m]$$

$$U_{overall} = \frac{1}{R_{total} \cdot UnitArea}$$

FIGURE 16: FINAL Q OUTPUT FOR THE SYSTEM

Reynolds Number Calculations

Temperature Difference of final house temperature

$$mdot_{house} = 1.3 \quad [kg/s]$$

Cp_{meth} =specheat(Water,T=Tinpod, P= 500 [kPa])

$$Cp_{meth2} = 4200 \quad [J/kg*K]$$

$$Tinpod = 10 \quad [C]$$

$$Tpodfluid2 = 11 \quad [C]$$

$$T_{solved} = Tinpod - (Tinpod - Tpodfluid2) \cdot \mathbf{exp}\left[\frac{\frac{1}{R_{total}}}{mdot_{house} \cdot Cp_{meth2}}\right]$$

Temperature out of well pipe

$$Twellwater2 = 13 \quad [C]$$

$$Cp_{water} = \mathbf{Cp}(water, T = Twellwater, P = 500 \quad [kPa])$$

$$Cp_{water2} = 4184$$

$$mdot_{well} = 0.032 \quad [kg/s]$$

$$Rwell = RW1 + RW2 + RW3$$

$$Tout_{well} = Twellwater2 - (Twellwater2 - Tpodfluid2) \cdot \mathbf{exp}\left[\frac{\frac{1}{Rwell}}{mdot_{well} \cdot Cp_{water2}}\right]$$

Demonstate Conservation of Energy - go through and show that the well is outputing X and the house recieves X

FIGURE 17: SOLVING FOR OUTPUT TEMPERATURE

BASELINE POD DESIGN RESULTS SUMMARY

The complete EES model contained a total of 96 variables for which it was determined given our baseline values for what was considered a simple model. The Parameters for Baseline Design (Table 6) contains all the key variables that were chosen for the baseline system. Given these values, the Q-total of the system was 755W. Which given the per-determined heating load of a home, a house would need approximately 4 pod's to heating the home throughout a winter. The main conclusion from modeling this pod was discovering the ground alone would be insufficient to heat a home. Given the results tabled below, the well supplied 82% of the Q-total of the pod.

PARAMETERS FOR BASELINE DESIGN		SPECIFICATION
POD PIPES		
	Length	25 m
	Material	Aluminum alloy
	Diameter	0.0229 m
	Mass Flow Rate	1.3 kg/s
	Working Fluid	Cacl2
POD		
	Wall Thickness	.01 m
	Model Shape	Sphere
	Radius	1 m
	Wall Material	Aluminum alloy
	Surround Medium	CaCl2
	Natural Convection Avg.	38 W/m^2*K
	Q from Pod	45.25 W
GROUND		
	Material	Silty Gravely Sand
	Temperature	10 C
	Q from Ground	87.01 W
WELL PIPES		
	Water temperature	12.7° C
	Length of well	25 m
	Diameter of well pipe	0.0229 m
	Mass Flow Rate	0.032 Kg/s
	Q from Well	622.8 W
OVERALL ENERGY OUTPUT OF POD		755 W

TABLE 6: PARAMETERS FOR BASELINE DESIGN

ESS Model Iterations

In order to test the sensitivity of the code and the variables in the code, various iterations with the different variables were made to the code. Many different values were plugged into the code to see how the final energy output (Q) in watts would be affected. Important to note, only 1 parameter was changed at a time, the rest were exactly as shown in the previous section.

Ground Material

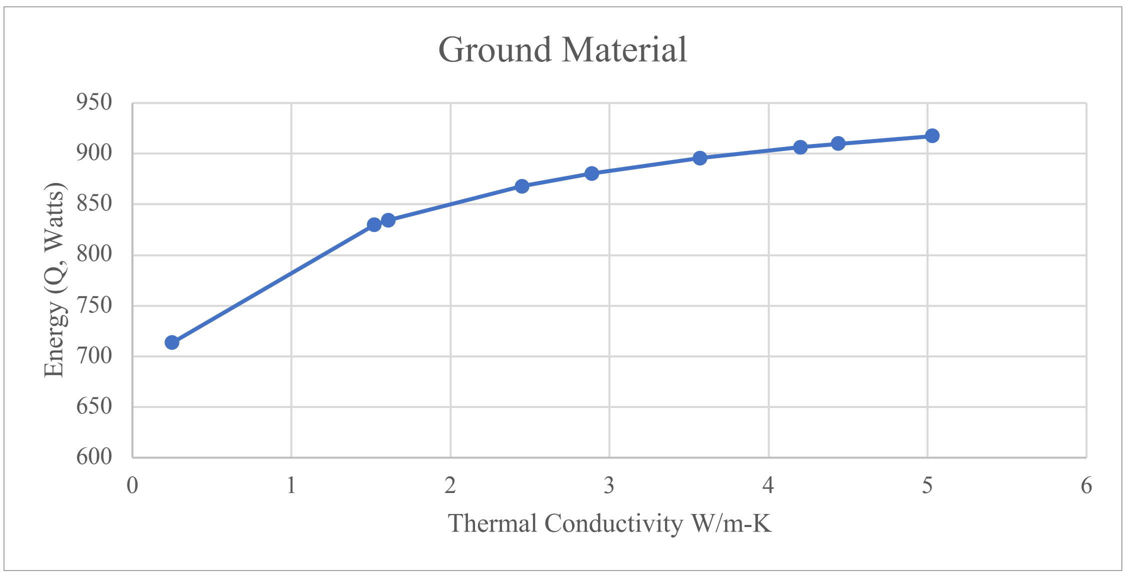


FIGURE 18: GRAPH OF THE RELATIONSHIP BETWEEN GROUND MATERIALS TO ENERGY OUTPUT

The ground material is not very sensitive in the system. The system gathers most of its energy from the well, not directly from the ground. There is a slight increase with the increase of thermal conductivity, but there is not much change once the K gets to around 4.2 W/m-K. The table of ground materials used in this iteration can be viewed in Appendix B.

POD PIPE LENGTH

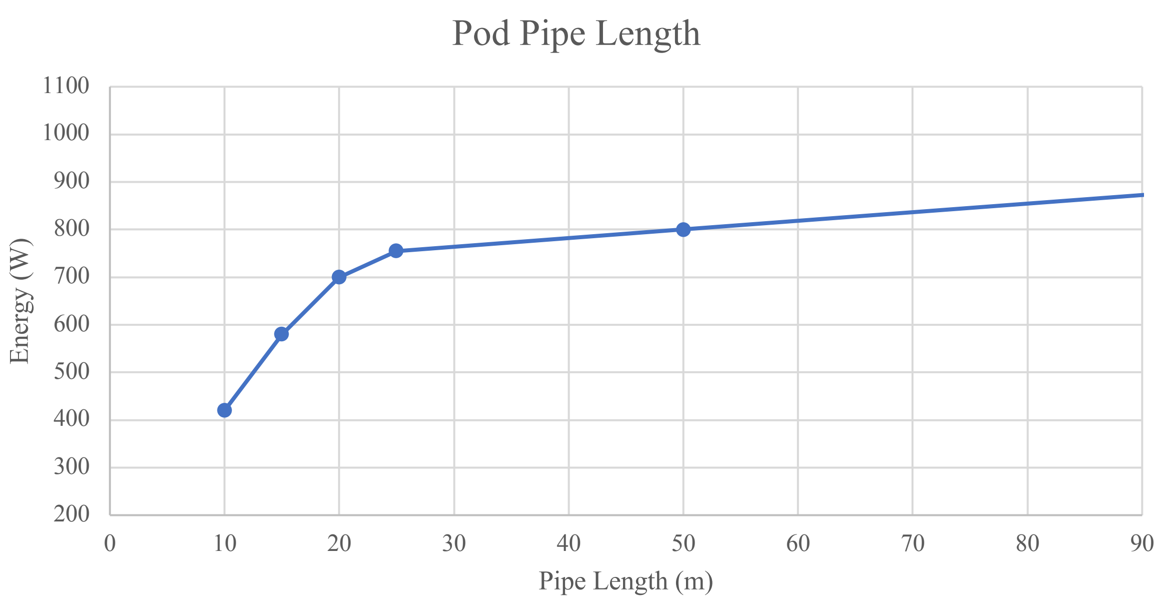


FIGURE 19: GRAPH OF THE RELATIONSHIP BETWEEN PIPE LENGTHS TO ENERGY OUTPUT

The pipe length increased the Q in a non-linear fashion. This makes sense because the more surface area the higher the heat transfer would generally increase, however, only to an extent due to the limitations of the system as the temperature delta between the pipe and the surrounding medium drops off for longer pipes. With the increase in pipe length, there is an increase in surface area between the 10m and 50m range where the energy output is doubled. After the 50m mark, the rate of change in Energy output by length is reduced, which is a key point for future design optimization of the Pod.

FORCED CONVECTION COEFFICIENT

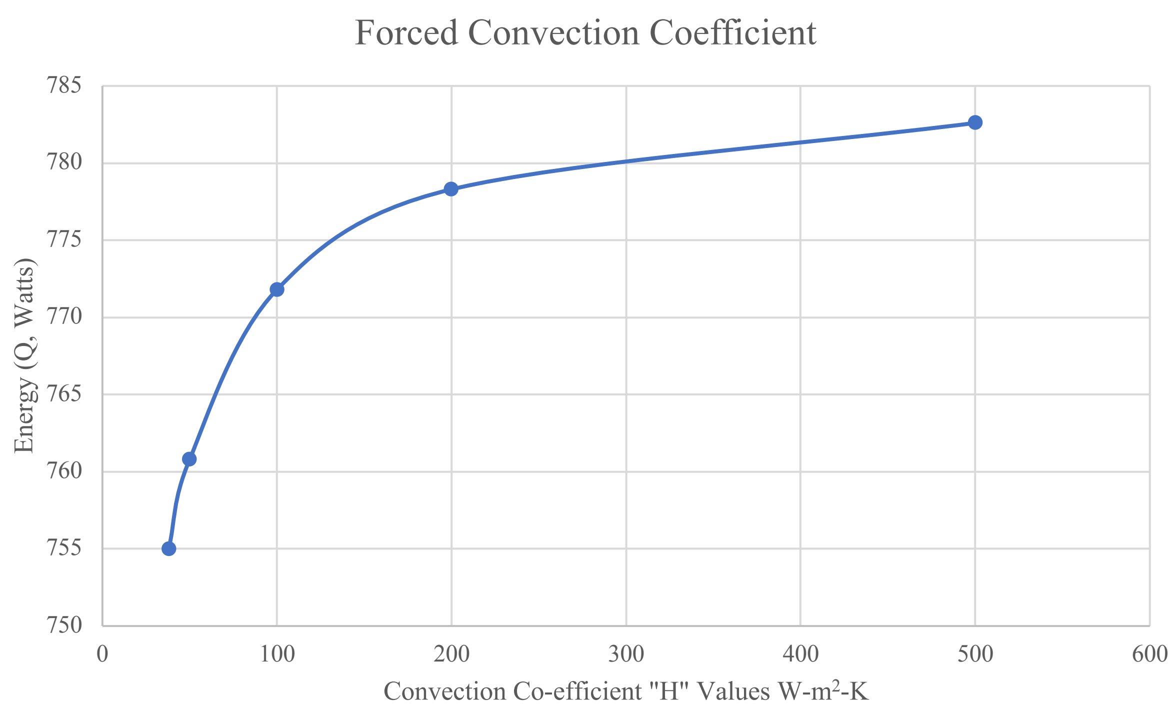


FIGURE 20: GRAPH OF THE RELATIONSHIP BETWEEN FORCED CONVECTION VALUES TO ENERGY OUTPUT

When altering the forced convection coefficient, the energy does increase with increasing H Values. The energy does reach a point of leveling out, at around 200 W-m^2-K. This is probably due to resistance value of forced convection being much less resistance than natural convection such that further reducing the resistance will have little effect on the system.

Flow Rate

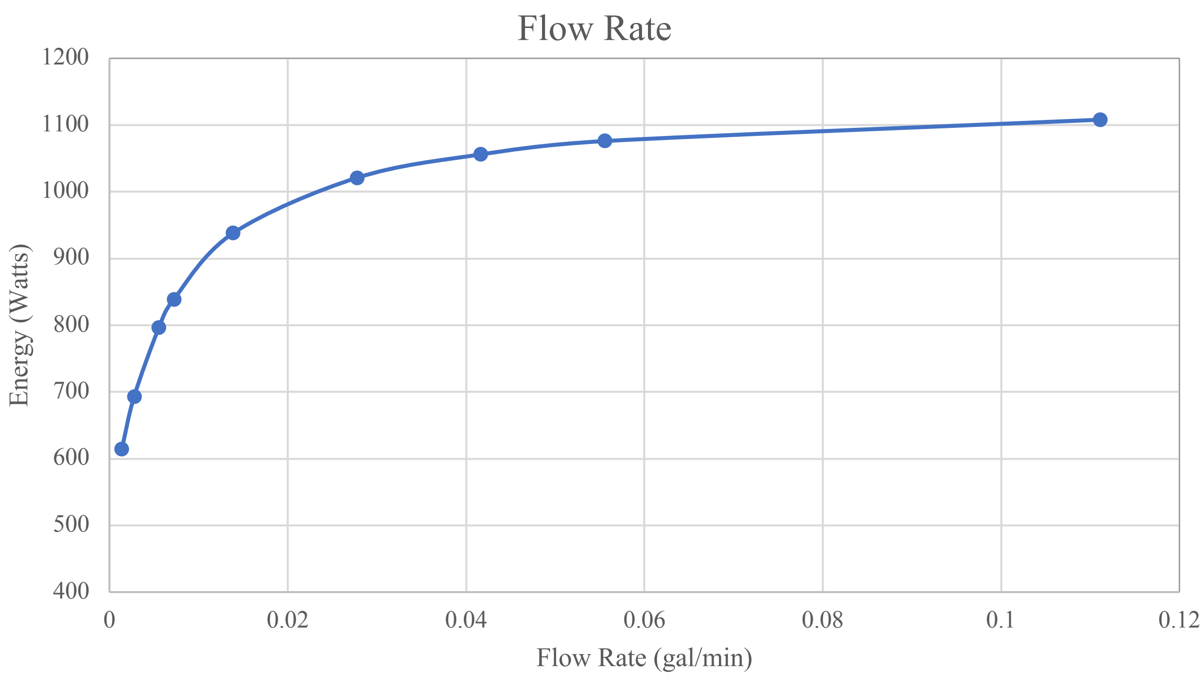


FIGURE 21: GRAPH OF THE RELATIONSHIP BETWEEN FLOW RATES TO ENERGY OUTPUT

The flow rate of the liquid in the pipes does have a significant effect on the energy of the system, but like many other variables it asymptotes out at about 0.055 GPM.

WELL WATER TEMPERATURE

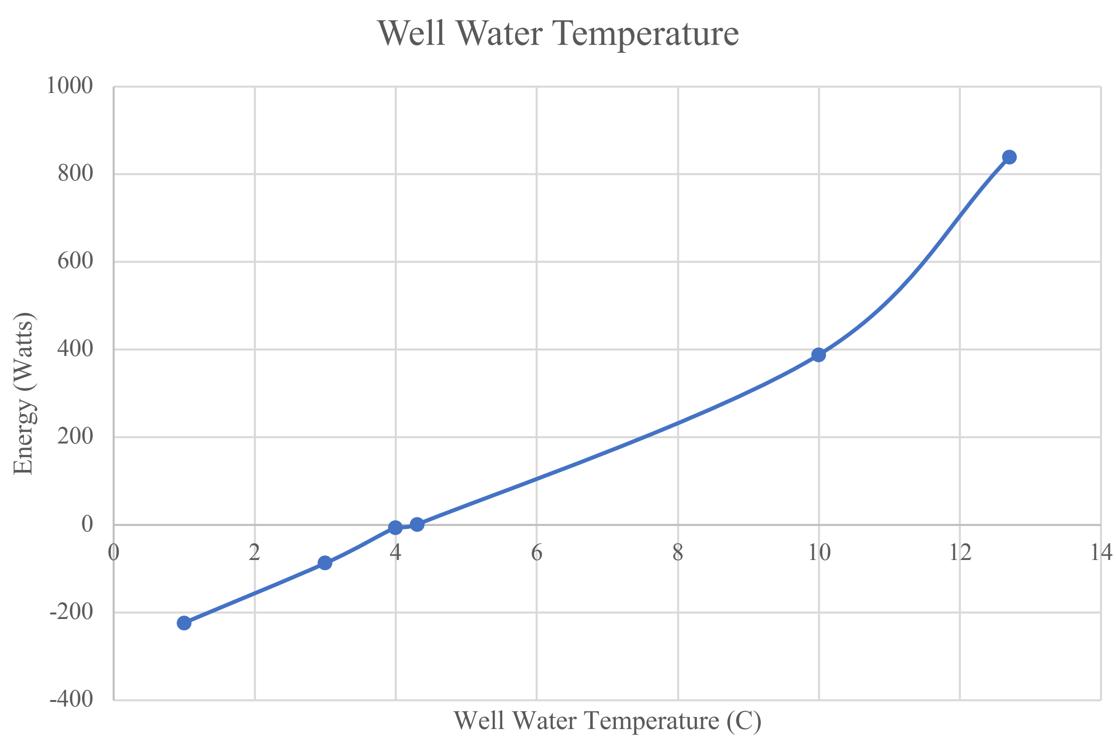


FIGURE 22: GRAPH OF THE RELATIONSHIP BETWEEN WELL WATER TEMPERATURES TO ENERGY OUTPUT

The well water temperature also has a great effect on the final Q value. The energy even dips below zero when approaching 0 degrees Celsius and turns positive at about 3.7 degrees Celsius.

Pod Thickness

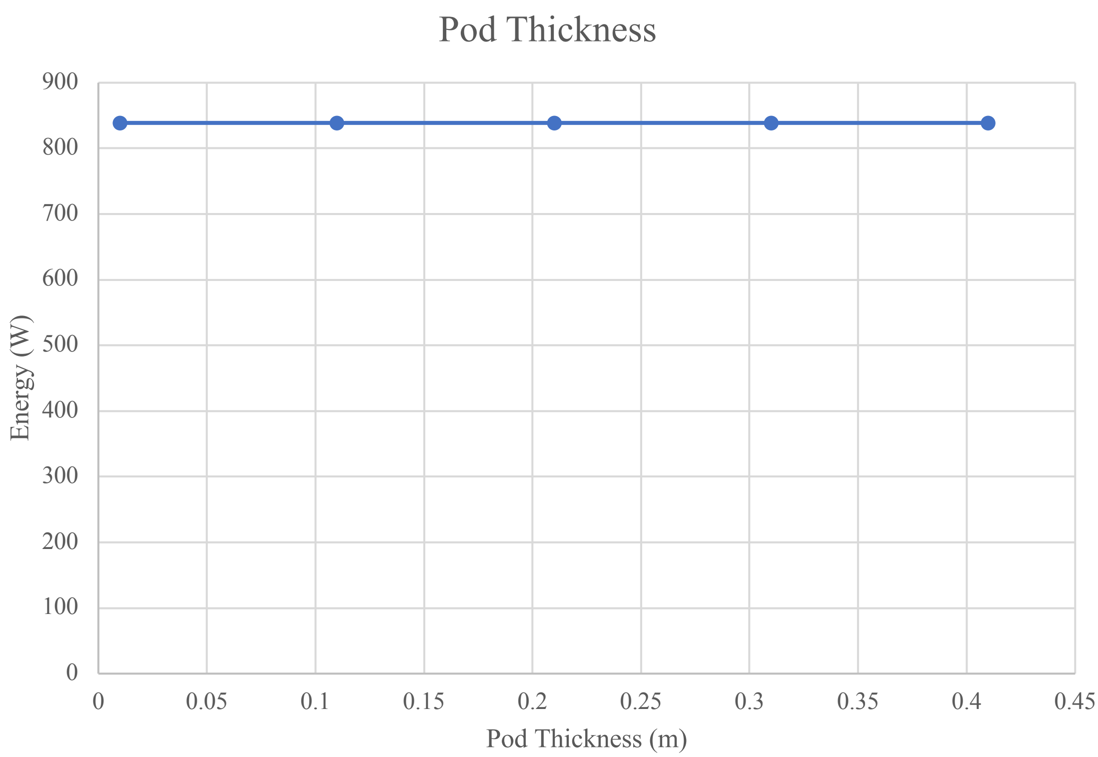


FIGURE 23: GRAPH OF THE RELATIONSHIP BETWEEN POD THICKNESSES TO ENERGY OUTPUT

The pod thickness does not affect the final energy value whatsoever. This is because the heat transfer from the ground to the pod wall and into the pod is not significant enough to make any difference.

Pod Radius

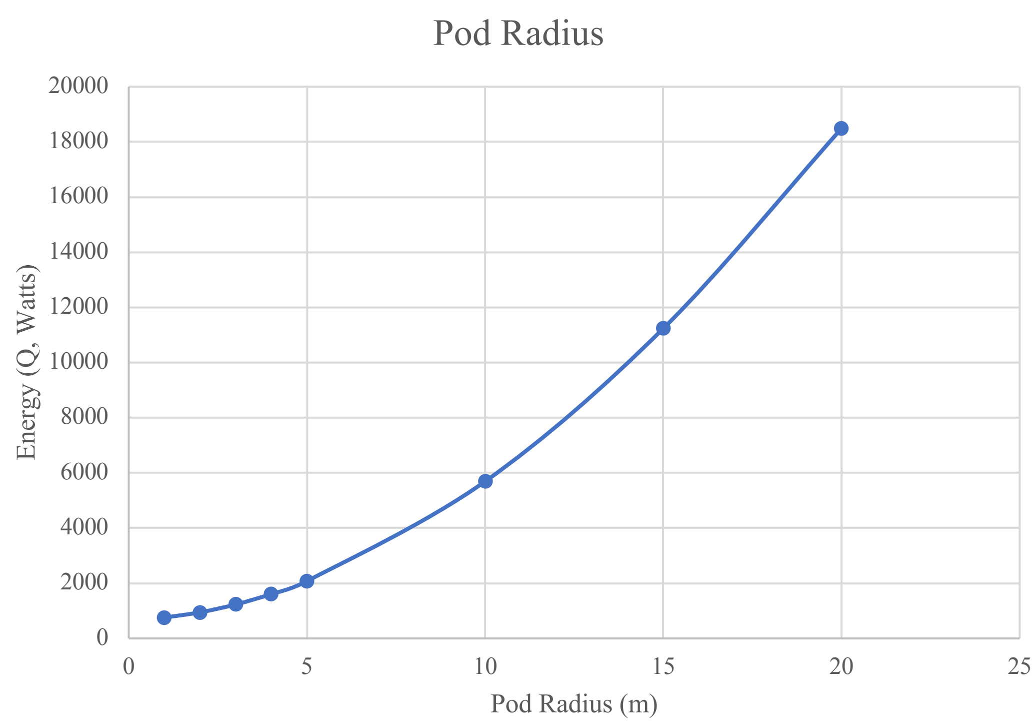


FIGURE 24: GRAPH OF THE RELATIONSHIP BETWEEN POD RADII TO ENERGY OUTPUT

The pod radius does have a tremendous effect on the final Q, but the reality of the situation is that it is un-realistic to have a pod of 20m radius. A 20-meter cubed pod would be impractical and negate the whole purpose of a modular heating system.

POD MATERIAL

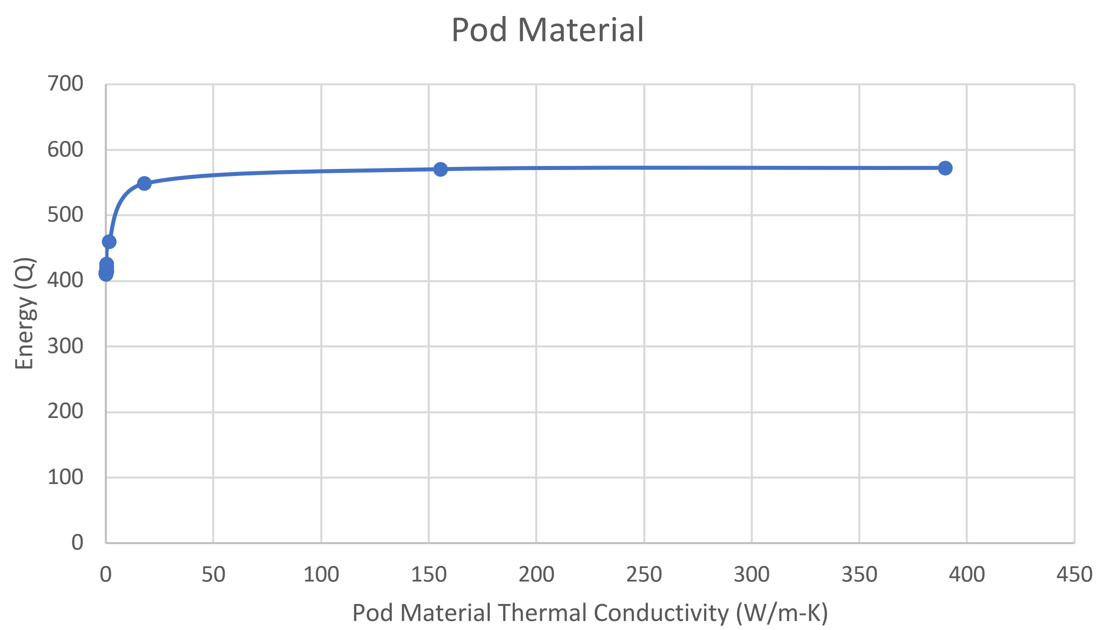


FIGURE 25: GRAPH OF THE RELATIONSHIP BETWEEN POD MATERIALS TO ENERGY OUTPUT

With the increase in thermal conductivity, the energy increases. The energy does asymptote out at 18 W/m-K. The table of the substituted materials can be seen in Appendix B.

WORKING FLUID

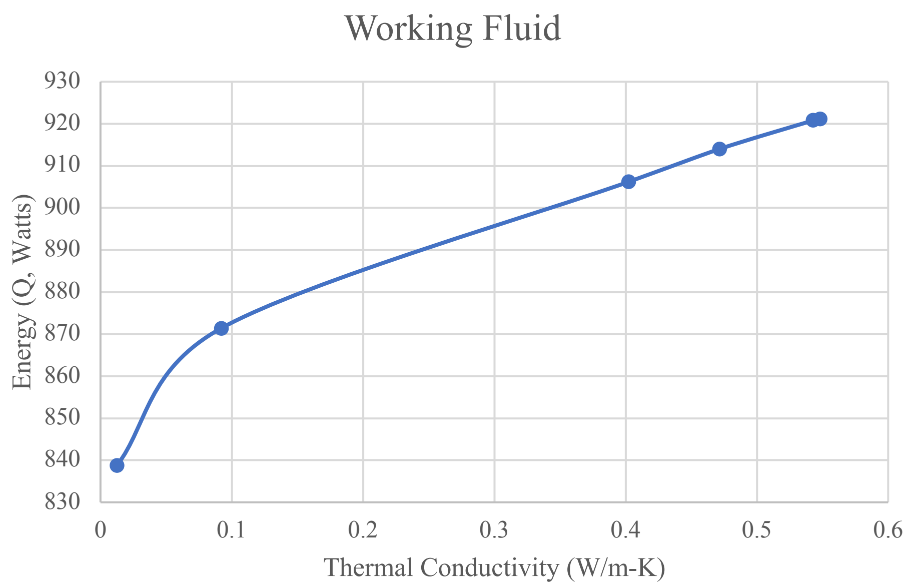


FIGURE 26: GRAPH OF THE RELATIONSHIP BETWEEN WORKING FLUID TO ENERGY OUTPUT

The working fluid affects the final energy output through the thermal conductivity. There are no great revelations in this iteration in regard to working fluid, they mostly are in 100 watts of each other. Since this iteration had a small effect on the rest of the system, a future design would have to take into consideration the toxicity and corrosiveness of the fluid. The table for working fluid can be found in Appendix B.

Surrounding Medium

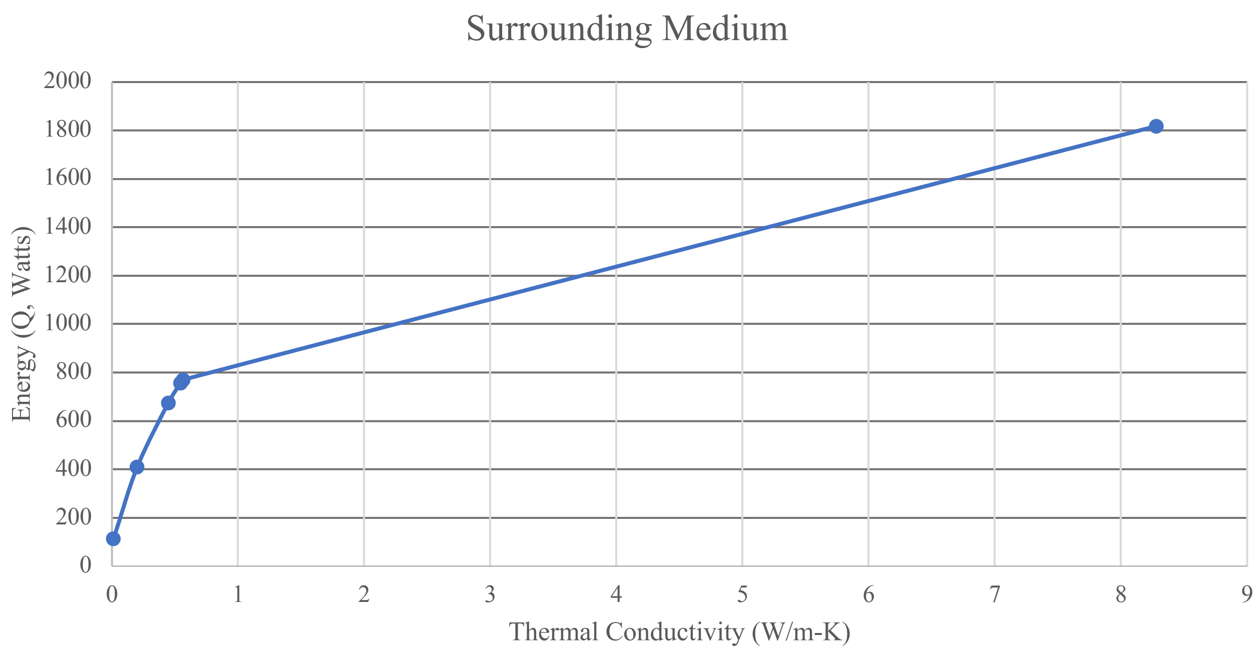


FIGURE 27: GRAPH OF THE RELATIONSHIP BETWEEN SURROUNDING MEDIUM TO ENERGY OUTPUT

The surrounding medium, or the surrounding liquid around the coiled pipes in the pod, does have a significant effect on the system. The higher the thermal conductivity, the higher the total energy, which intuitively makes sense. Mercury raises the energy by almost three-fold but is impractical because of health and environmental reasons. The liquids that were iterated are present in the table in Appendix B.

Optimized Pod Design Results Summary

The following section breaks down the design specifications of the modular geothermal heat pump system. These specifications, outlined in Table 7 and Table 8 were chosen to maximize the energy output while also reducing costs and ensuring longevity of the system. The design parameters chosen for the optimized pod design are highlighted with red text.

TABLE 7: LAYOUT OF ALL CHOICES FOR THE OPTIMIZED POD DESIGN

Iterated Parameter (Figure)	**Iterated Parameter Values**							**Units**
Pod pipe length (Figure 19)	10	15	20	25	35			m
Pod thickness (Figure 23)	.01	.11	.21	.31	.41			m
Pod material (Figure 25)	PC+PBT	PC+PET	PC	ABS (glass)	PMMA	PVC	PC (glass, silicon)	
	PC (glass)	ABS+PVC	ABS (steel)	Polyester	ABS (aluminum)	PVC (glass)	ABS (carbon)	
	Stainless steel	Aluminum alloy	Copper alloy	ABS+PC	Concrete	ABS	PC (carbon)	
Ground material (Figure 18)	China clay (dry)	China clay (sat.)	Sandy clay	Sandy clay 2	BH C13 88	Soft dark gray clay	Soft gray fine clay	
	Gray slightly silty gravel	Silty gravely sand						
Flow rate (Figure 21)	0.0014	0.0028	0.0056	0.0072	0.0139	0.0278	0.0417	GPM
	0.0556	0.1111						
Well water temperature (Figure 22)	1	3	4	4.3	10	12.7		C
Working fluid (Figure 26)	$CaCl_2$	EA	Glycerol	Water	K_2CO_3	Methanol	R134a	
Pod radius (Figure 24)	1	2	3	4	5	10	15	m
	20							
Surrounding medium (Figure 27)	R134a	Methanol	$MgCl_2$	$CaCl_2$	Water	Mercury		
Forced convection values (Figure 20)	38	50	100	200	500			Wm^2K

Figure 19 shows that as length of pod pipe increases, so does the energy output; we chose to use the largest value of pipes that we iterated, 35 m. However, the true optimal choice would be as many much piping that could fit into the pod. Figure 23 shows that pod thickness isn't a huge determining factor in the energy output; we chose the lowest value of .01 m to conserve material and costs.

Figure 25 shows that as thermal conductivity for the pod material increases, so does the energy output; however, we chose to use aluminum alloy to conserve costs even though it does not have the highest thermal conductivity. Figure 18 shows that a silt gravel sand mix maximizes the energy output so it was chosen for the optimal system. In reality, the ground composition is not something we can necessarily control so this would need to be changed in real life applications. Figure 21 shows that flow rate has a direct relationship with the energy output; thus the largest value of 0.1111 GPM was selected. Figure 19 shows that 12.7°C maximizes the energy output, but 13°C was used in the optimal design due to independent temperature calculations. Figure 26 and Figure 22 show that methanol and a forced convection value of 200 W/m^2K respectively increased the energy output the most. Figure 24 shows that as pod radius increases, so does the energy output. However, because we want the system to be small and modular, we chose the value of 1 m for the pod radius. $CaCl_2$ was chosen for the surrounding medium because it produced the most energy outputted without issues of toxicity (See Figure 27).

PARAMETERS FOR OPTIMIZED DESIGN		SPECIFICATION
POD PIPES		
	Length	35 m
	Material	Aluminum alloy
	Diameter	0.0229 m
	Flow rate	0.1111 GPM
	Working fluid	Methanol
POD		
	Thickness	.01 m
	Shape	Sphere
	Radius	1 m
	Material	Aluminum alloy
GROUND		
	Material	Silty Gravely sand
	Temperature	10 C
WELL		
	Water temperature	12.7° C
	Length of well (depth)	35 m
	Diameter of well pipe	0.0229 m
OTHERS		
	Surrounding medium	$CaCl_2$
	Forced convection value	200 W/m^2K
OVERALL ENERGY OUTPUT OF OPTIMIZED POD		1594 W

TABLE 8: BREAKDOWN OF THE OPTIMALLY DESIGNED SYSTEM AND OUTPUTTED ENERGY

The modular geothermal heat pump system that was designed with the optimal design choices can produce 1,594 Watts of outputted energy to the house. As stated before the house requires 11,067.35 BTU/hr or 3,242.7 Watts. This means that one unit of the geothermal system cannot meet the energy demand alone. Instead, 3 of these modular units need to be put together to produce over the required 3,242.7 Watts. Additional units can be added if more energy is needed for a larger home. Similarly, smaller homes would require a smaller number of units.

Typical residential water well with a six-inch diameter has a minimum water flow rate of 5 gallons/minute (GPM) (“Recommended Minimum Water Supply Capacity for Private Wells”, 2010). Using the equation of E=Cp*dT*m at 11,067.35 BTU/hr over a 24-hour period, the water needed per day is 518.1 gallons. Pumping at a minimum of 5 GPM, the well will only need to pump 1.73 hours/day to meet this water demand. This is a practical request that a water well can tolerate.

CONCLUSION

Currently in the United States, modern geothermal heating systems have not been widely adopted. The main difficulty with using geothermal systems in the Northeast is due to low ground temperatures and steep installation costs ("Energy Environmental", 2018). The goal of the project was to develop a mathematical model, for which it was used to adapt the traditional geothermal system to a modular pod system. Upon completion of the project, the goal has been achieved of designing a new pod style geothermal system that is an advancement to traditional geothermal systems.

Throughout the project, there were a variety of key design points which were modified to improve the overall function of the system. The most significant finding was realizing that the ground would not transfer the pod enough energy to heat the model house, for a winter season. In order to ensure the model would initially receive enough natural energy, a well was incorporated into the model. The amount of energy available from the water in the well allowed the pod to transfer sufficient energy to the house, for which in turn satisfied the average winter heating requirement.

The next major finding was that the optimized system which included all of the maximized output values for each parameter. The final optimized system output as previously discussed totaled to 1,594 watts. This is about double our base system output of 755 watts and allows for other design aspects to be considered such as cost and manufacturability. This concludes that three pods are more than enough to meet the heating load required for a typical house.

In addition to iterating the optimized system, there were a variety of parameters that did not largely affect the output of the ESS model. For example, the pod wall thickness and the material of the pod had minimal difference to the total energy out of the system. It was also discovered that is was not effective to use a PCM as the surrounding medium of the pipes because there was no suitable PCM that could transition within the temperature range of operation and PCMs cannot store enough energy, at a reasonable size to burry underground, to eliminate the need for a well. The system is primarily sensitive to the thermal conductivity material of the ground. Unfortunately, the New England area does not have a wide range of ground thermal conductivities which is another reason geothermal systems are not common in this part of the country.

RECOMMENDATIONS

Based on our conclusions, the team developed a series of recommendations to future teams on this project. Initially given the optimized system as previously described, it would be beneficial to build a physical model of the optimized system for the next stage of development. Building a physical model would help verify the mathematical model. Within the EES code, we provided all the different materials to use and the quantities needed to create this system. Testing of the model in the ground is recommended, in addition to completing a variety of ground material testing to determine an alternative method to placing the pod directly in typical soil mixtures. To conclude, further research is suggested to expand on the material lists for this system. Although there was an extensive amount of research to the materials that were involved in the system, there are thousands of different materials, all with their own advantages and disadvantages such as corrosion, manufacturability and even cost were not widely considered in the present study. Materials were chosen for what would be the best for an optimized system, but these material selections can always be improved. The EES model will be continuing to be updated as physical testing is complete along with a detailed cost analysis of the short and long-term functionality of this system.

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APPENDIX A: IMPORTANT FIGURES AND TABLES FOR PCMS

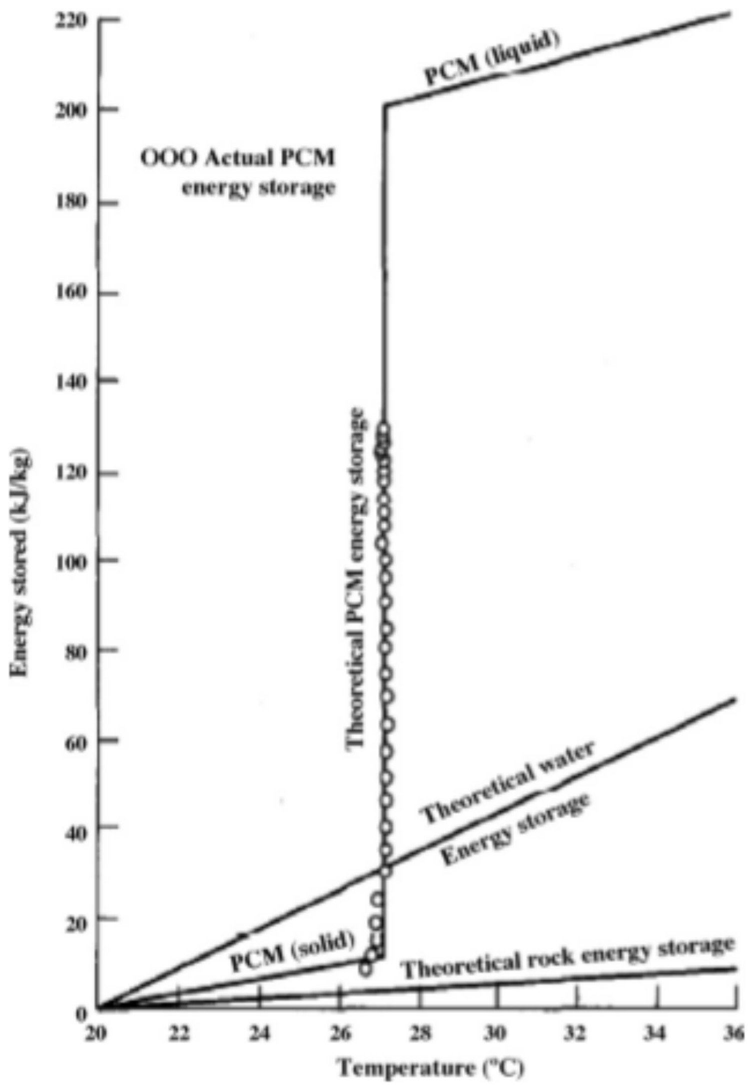

Fig. 6. Performance comparison of PCM, water and rock storage system.

Source: Review on Thermal Energy Storage with Phase Change Materials and Applications

(Atul Sharma, V.V. Tyagi, C.R. Chen, & D. Buddhi,) Organic substances with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
Paraffin C_{14}	4.5 [1]	165 [1]	n.a.	n.a.
Paraffin C_{15}–C_{16}	8 [1]	153 [1]	n.a.	n.a.
Polyglycol E400	8 [4,11]	99.6 [4,11]	0.187 (liquid, 38.6 °C) [4,11] 0.185 (liquid, 69.9 °C) [11]	1125 (liquid, 25 °C) [4,11] 1228 (solid, 3 °C) [4,11]
Dimethyl-sulfoxide (DMS)	16.5 [28]	85.7 [28]	n.a.	1009 (solid and liquid) [28]
Paraffin C_{16}–C_{18}	20–22 [29]	152 [29]	n.a.	n.a.
Polyglycol E600	22 [4,11]	127.2 [4,11]	0.189 (liquid, 38.6 °C) [4,11] 0.187 (liquid, 67.0 °C) [11]	1126 (liquid, 25 °C) [4,11] 1232 (solid, 4 °C) [4,11]
Paraffin C_{13}–C_{24}	22–24 [1]	189 [1]	0.21 (solid) [1]	0.760 (liquid, 70 °C) [1] 0.900 (solid, 20 °C) [1]
1-Dodecanol	26 [9]	200 [9]	n.a.	n.a.
Paraffin C_{18}	28 [1] 27.5 [30]	244 [1] 243.5 [30]	0.148 (liquid, 40 °C) [30] 0.15 (solid) [1] 0.358 (solid, 25 °C) [30]	0.774 (liquid, 70 °C) [1] 0.814 (solid, 20 °C) [1]
1-Tetradecanol	38 [9]	205 [9]		
Paraffin C_{16}–C_{28}	42–44 [1]	189 [1]	0.21 (solid) [1]	0.765 (liquid, 70 °C) [1] 0.910 (solid, 20 °C) [1]
Paraffin C_{20}–C_{33}	48–50 [1]	189 [1]	0.21 (solid) [1]	0.769 (liquid, 70 °C) [1] 0.912 (solid, 20 °C) [1]
Paraffin C_{22}–C_{45}	58–60 [1]	189 [1]	0.21 (solid) [1]	0.795 (liquid, 70 °C) [1] 0.920 (solid, 20 °C) [1]
Parffin wax	64 [4,11]	173.6 [4,11] 266 [6]	0.167 (liquid, 63.5 °C) [4,11] 0.346 (solid, 33.6 °C) [4,11] 0.339 (solid, 45.7 °C) [11]	790 (liquid, 65 °C) [4,11] 916 (solid, 24 °C) [4,11]
Polyglycol E6000	66 [4,11]	190.0 [4,11]	n.a.	1085 (liquid, 70 °C) [4,11] 1212 (solid, 25 °C) [4,11]
Paraffin C_{21}–C_{50}	66–68 [1]	189 [1]	0.21 (solid) [1]	0.830 (liquid, 70 °C) [1] 0.930 (solid, 20 °C) [1]
Biphenyl	71 [4,11]	119.2 [4,11]	n.a.	991 (liquid, 73 °C) [4,11] 1166 (solid, 24 °C) [11]
Propionamide	79 [11]	168.2 [11]	n.a.	n.a.
Naphthalene	80 [4,11]	147.7 [4,11]	0.132 (liquid, 83.8 °C) [4,11] 0.341 (solid, 49.9 °C) [4,11] 0.310 (solid, 66.6 °C) [11]	976 (liquid, 84 °C) [4,11] 1145 (solid, 20 °C) [4,11]
Erythritol	118.0 [31]	339.8 [31]	0.326 (liquid, 140 °C) [31] 0.733 (solid, 20 °C) [31]	1300 (liquid, 140 °C) [31] 1480 (solid, 20 °C) [31]
HDPE	100–150 [32]	200 [32]	n.a.	n.a.
Trans-1,4-polybutadiene (TPB)	145 [33]	144 [33]	n.a.	n.a.

Source: Review on Thermal Energy Storage with Phase Change Materials and Applications

(Atul Sharma, V.V. Tyagi, C.R. Chen, & D. Buddhi,)

APPENDIX B: MATERIAL TABLES FOR GRAPHS

The values for thermal conductivity for the pod material mathematical iterations are listed below with appropriate energy output results used to make Figure 25.

Pod Material	Thermal Conductivity K (W/m-K)	Energy Q (Watts)
PC+PBT blend (unfilled)	0.18	410.4
PC+PET blend (unfilled)	0.19	410.9
PC (unfilled)	0.197	411.2
ABS (20% glass)	0.201	411.4
PMMA (unfilled)	0.21	411.9
PVC (unfilled)	0.22	412.4
PC (30% glass, 2% silicon)	0.2325	413
ABS (unfilled)	0.258	414.2
ABS+PC (unfilled)	0.267	414.6
PC (10% glass)	0.268	414.7
ABS+PVC blend (unfilled)	0.2695	414.7
ABS (7% stainless steel)	0.2815	415.3
Polyester (unfilled)	0.293	415.9
ABS (40% aluminum flake)	0.3005	416.2
PVC (20% glass)	0.3865	420.1
ABS (20% carbon)	0.402	420.8
PC (20% carbon)	0.5205	425.9
Concrete	1.6	460
Stainless Steel	18	548.6
Aluminum Alloys	155.5	570.5
Copper Alloys	390	572.5

The values for thermal conductivity for the ground material mathematical iterations are listed below with appropriate energy output results used to make Figure 18 (Hamdhan, 2010).

Ground Material	Thermal Conductivity K (W/m-K)	Energy Q (Watts)
China Clay (D) (Dry)	0.25	713.4
China Clay (D) (Sat.)	1.52	829.7
Sandy Clay	1.61	834.4
Sandy Clay 2	2.45	867.9
BH C13 88	2.89	880.4
Soft Dark Gray Sandy Gravely Clay	3.57	895.5
Soft Gray Fine Sandy Clay	4.2	906.3
Gray Slightly Silty Sandy Gravel	4.44	909.8
Silty Gravely Sand	5.03	917.3

The values for thermal conductivity for the working fluid mathematical iterations are listed below with appropriate energy output results Figure 26.

Working Fluid	Thermal Conductivity K (W/m-K)	Energy Q (Watts)
Brine/$CaCl_2$	0.01267	838.8
Ethyl Alcohol-Water (EA)	0.09202	871.4
Glycerol	0.4023	906.2
Water	0.4715	914
K_2CO_3	0.543	920.8
Methanol	0.548	921.2
R134a	0.1	803.8

The values for thermal conductivity for the surrounding medium mathematical iterations are listed below with appropriate energy output results Figure 27.

Surrounding Medium	**Thermal Conductivity K** (W/m-K)	**Energy Q** (Watts)
R134a	0.01267	112.8
Methanol	0.1997	408.6
$MgCl_2$	0.4463	673.8
$CaCl_2$	0.543	755
Water	0.562	769.9
Mercury	8.279	1818

APPENDIX C: COMPLETE EES CODE

```
"General Q calculations for determining the energy needed from ground to working fluid of the system."
    "Part Well: Given Values for Resistance"
    "Part Ground: Establish Resistance Equations"
    "Part Pod"
    "Part Final Q Equations Q=dT/Rtotal"


"%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


">>>>>>>>>>>>>>>>R _ WELL >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>"

"Well INPUTS"
    Twellwater = 12.7 [C]
    Pwell = 344 [kPa]   "50 psi"

    Tpodliquid = 7.2 [C]
    Tpodpipe = 7 [C]

    Ppod = 262 [kPa] "38psi which is 2psi below cut-in for a 40/60 tank pressure"

    Do_wellpipe = 0.025 [m]
    Di_wellpipe = 0.0229 [m]

    L_well = 25 [m]     "Length of pipe inside of pod"

    g = 9.81 [m/s^2]

    Kal = conductivity(Aluminum, T=Tpodliquid)
    Kwater =conductivity(Water,T=Twellwater,P=Pwell)
    Kwater_pod = conductivity(Water,T=Tpodliquid,P=Ppod)
    "Kmeth_pod = conductivity(Methanol,T=Tpodliquid,P=Ppod)"
    Kr134a_pod = conductivity(R134a,T=Tpodliquid,P=Ppod)
    Knacl_pod = conductivity(NaCl,T=Tpodliquid,C=30[%])
    kcacl2_pod = conductivity(CaCl2,T=Tpodliquid,C= 30 [%])
    kmgcl2 = conductivity(MgCl2,T=Tpodliquid,C=30[%])
    Kmercury = conductivity(Mercury_liquid, T=TpodLiquid)
    Kox = conductivity(O2,T=Tpodliquid)
    Khe = conductivity(He,T=Tpodliquid)
    Kea = conductivity(EA,T=Tpodliquid,C= 30 [%])
    Kk2co3 = conductivity(K2CO3,T=Tpodliquid,C= 30 [%])
    Kglyc = conductivity(GLYC,T=Tpodliquid,C= 30 [%])
```

```
beta_br = volexpcoef(Water,T=Tpodliquid,P=Ppod)
nu_br = kinematicviscosity(CaCl2,T=Tpodliquid,C=30 [%])
alpha_br = thermaldiffusivity(CaCl2,T=Tpodliquid,C=30 [%])

kcacl2_br =conductivity(CaCl2,T=Tpodliquid,C= 30 [%])
cp_br=specheat(CaCl2,T=Tpodliquid,C= 30 [%])
mu_br=viscosity(CaCl2,T=Tpodliquid,C= 30 [%])

Excel_h = 1598  "h for water inside well pipes based on correlations"

Pod_fluid = Kcacl2_pod

Podwall_mat = Kal

"RW1 Well Water Resistance"
   "hW1 = (Nuss_inwellpipe * Kwater)/Di_wellpipe"
   hW1 = Excel_h*(6/100)
   RW1 = 1/(hW1 * 2* pi * Di_wellpipe * L_well)

"RW2: Well Pipe Wall Resistance"
   RW2 = ln(Di_wellpipe/Do_wellpipe)/(2*pi*L_well*PodWall_mat)


"RW3 Pipe to Brine Resistance -Natural Convection"

   "Caluclate Ra using beta and nu and alpha pg 492"
   Ray_W3 =  (g*beta_br*(Tpodliquid - Tpodpipe)*(Do_wellpipe^3))/(nu_br*alpha_br)


   "Prandtl Number Equation from Wiki"
   Pr_W3 = nu_br / alpha_br

   "pg502 use brine properties to define Ra and Pr"
   Nuss_outsidewellpipe =(0.60 + (0.387*Ray_W3^(1/6))/((1+(0.559/Pr_W3)^(9/16))^(8/27)))^(2)

   "area is entire surface are of the pipe based on pipe length and diameter"
   AW3 = Pi*L_well*Do_wellpipe
   hW3 =  (Nuss_outsidewellpipe*Pod_fluid)/Do_wellpipe
   RW3 = 1 / (hW3 * AW3)

">>>>>>>>>R_GROUND >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>"

"INPUTS:"
   Tground = 10 [C]  "Temperature of Ground"

   Kground = 1.7      "Water saturated clay/silt from Ground Thermal Diffusivity Calculation by Direct Soil Temperature Measurement."

   rs1 = 2  [m]   "radius of outer sphere for ground model"

   Ground_thickness = 1 [m]

   AG3 = Pi*(rs1 - ground_thickness)^2   "Area of Pod Liquid"

   hG3v = 35    "h value from a vertical plate"    " Givens For Online Calculators: "

   hG3h = 41    "h value from a horizontal plate with hot side up"

   Pod_thickness = 0.01 [m]

   pod_material = Kal

"RG1 Ground Info : Modeled as Sphere"

   rs2= rs1 - ground_thickness "Inner radius of the ground sphere in model aka the size of the POD, and ground-thickness changes "

   RG1 = (rs1 -rs2)/(4*pi*rs1*rs2*Kground)


"RG2: Pod Wall Info (Modeled as a Sphere)"       "add Shape Factor"

   rp2= rs2 - Pod_thickness " radius of inner pod (.01 thickness) and old rp1= current rs2)"

   RG2_sphere = (rs2 -rp2)/(4*pi*rs2*rp2*pod_material)  "Sphere"
```

```
"-------------------shape factor-----------------"

D = (rs2)*2
z = rs1 + 1 [m]   "rs1 is input"

S = (2*pi*D)/(1 + (0.25*D/z))

"Qpodwall = S*kal*(Tg1 - Tg2)  is the shape factor equation which means --> [R = 1/SK]"

RG2_sfactor = 1 / (S*pod_material)

"RG3: Pod Liquid Info"

hG3avg = (hG3v + hG3h)/2

"h_forced = 200 [W/m^2*K]"

RG3 =1 / (hG3avg * AG3)

">>>>>>>>R_POD >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>"

"Tpodliquid = 7.2 [C] defined above Ppod definied above"
Tworkingfluid = 6 [C]

Do_podpipe = 0.025 [m]      "Pipe Diameter  inside the POD "
Di_podpipe = 0.0229 [m]

P_workingfluid = 379.2

L_podpipe = 25 [m]

PodPipe_mat = Kal

Kmeth_wf = conductivity(R134a,T=Tworkingfluid,P=P_workingfluid)

WorkingFluid = Kmeth_wf

"RP1 House Pipes to Brine Resistance - Natural Convection"

"Caluclate Ra using beta and nu and alpha pg 492"
Ray_P1 =  (g*beta_br*(Tpodliquid - Tpodpipe)*(Do_podpipe^3))/(nu_br*alpha_br)

"Prandlts Number"
Pr_P1 = nu_br / alpha_br

"pg502 use brine properties to define Ra and Pr"
Nuss_outsidepodpipe =(0.60 + (0.387*Ray_P1^(1/6))/((1+(0.559/Pr_P1)^(9/16))^(8/27)))^(2)

"area is entire surface are of the pipe"
AP1 = L_podpipe*Pi*Do_podpipe

hP1 =  (Nuss_outsidepodpipe*Pod_fluid)/Do_podpipe

R_P1 = 1 / (hP1 * AP1)

"RP2: Pipe Wall Resistance"

R_P2 = ln(Di_podpipe/Do_podpipe)/(2*pi*PodPipe_mat*L_podpipe)

"RP3: Pipe Working Fluid Resistance"

Nuss_inpodpipe = 3.36

hP3 = (Nuss_inpodpipe * WorkingFluid)/Di_podpipe

R_P3 = 1 / (hP3 * 2* pi * Di_podpipe * L_podpipe)

"%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%"
```

```
"PART3: Final Q output for System"

"Q_ground"
"Temps: 50F to 45F "
    "Temp-in = Tground"
    "Temp-out = Tpodliquid"
"R-values: RG1, RG2, RG3"
Q_ground = (Tground - Tpodliquid) / (RG1 + RG2_sfactor + RG3)

"Q_well"
"Temps: 55F to 45F "
    "Temp-in = Twellwater"
    "Temp-out = Tpodliquid"
"R-values: RW1, RW2, RW3"
Q_wellR = RW1 + RW2 + RW3
Q_well = (Twellwater - Tpodliquid) / (RW1 + RW2 +RW3)

"Q_pod"
"Temps: 45F to 40F"
    "Temp-in = Tpodliquid"
    "Temp-out = Tworkingfluid"
"R - values: RP1, RP2, RP3"
Q_pod = (Tpodliquid - Tworkingfluid)/(R_P1 + R_P2 + R_P3)


"Total Q:"
Q_total=Q_ground+Q_well+Q_pod


R_total = RG1 + RG2_sfactor + RG3 + RW1 + RW2 +RW3 + R_P1 + R_P2 + R_P3


UnitArea = 1 [m]

U_overall = (1/(R_total*UnitArea))

"%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%"

"Reynolds Number Calculations"


"Temperature Difference of final house temperature"

mdot_house = 1.3 [kg/s]

"Cp_meth =specheat(Water,T=Tinpod, P= 500 [kPa])"

Cp_meth2 = 4200 [J/kg*K]

Tinpod = 10 [C]

Tpodfluid2 = 11 [C]

T_solved = Tinpod - (Tinpod - Tpodfluid2) * exp((1/R_total)/(mdot_house * Cp_meth2))

"Temperature out of well pipe"

Twellwater2 = 13 [C]

Cp_water = cp(Water,T=Twellwater, P = 500 [kPa])

Cp_water2 = 4184

mdot_well = 0.032 [kg/s]

Rwell = RW1 + RW2 + RW3

Tout_well = Twellwater2 - (Twellwater2 - Tpodfluid2)*exp( (1/Rwell) / (mdot_well * Cp_water2) )


"Demonstate Conservation of Energy - go through and show that the well is outputing X and the house recieves X"
```

APPENDIX D: BASELINE EES CODE RESULTS

Unit Settings: SI C kPa kJ mass deg

AG3 = 3.142 [m^2]	α_{br} = 1.541E-07 [m^2/s]	AP1 = 1.963 [m^2]	AW3 = 1.963 [m^2]
β_{br} = 0.0000469 [1/C]	cp_{br} = 2.736 [kJ/Kg*K]	Cp_{meth2} = 4200 [J/kg*K]	Cp_{water} = 4.184 [kJ/kg*K]
Cp_{water2} = 4184 [J/kg*K]	D = 2 [m]	$Di_{podpipe}$ = 0.0229 [m]	$Di_{wellpipe}$ = 0.0229 [m]
$Do_{podpipe}$ = 0.025 [m]	$Do_{wellpipe}$ = 0.025 [m]	$Excel_h$ = 1598 [W/m^2*K]	g = 9.81 [m/s^2]
$Ground_{thickness}$ = 1 [m]	hG3avg = 38 [W/m^2*K]	hG3h = 41 [W/m^2*K]	hG3v = 35 [W/m^2*K]
hP1 = 85.82 [W/m^2*K]	hP3 = 13.5 [W/m^2*K]	hW1 = 95.88 [W/m^2*K]	hW3 = 85.82 [W/m^2*K]
Kal = 233.8 [W/m-K]	$kcacl2_{br}$ = 0.543 [W/m-K]	$kcacl2_{pod}$ = 0.543 [W/m-K]	Kea = 0.4023 [W/m-K]
Kglyc = 0.4715 [W/m-K]	Kground = 1.7 [W/m-K]	Khe = 0.1446 [W/m-K]	Kk2co3 = 0.548 [W/m-K]
Kmercury = 8.279 [W/m-K]	$Kmeth_{wf}$ = 0.09202 [W/m-K]	kmgcl2 = 0.4463 [W/m-K]	$Knacl_{pod}$ = 1 [W/m-K]
Kox = 0.0253 [W/m-K]	$Kr134a_{pod}$ = 0.01267 [W/m-K]	Kwater = 0.5727 [W/m-K]	$Kwater_{pod}$ = 0.562 [w/m-K]
$L_{podpipe}$ = 25 [m]	L_{well} = 25 [m]	$mdot_{house}$ = 1.3 [kg/s]	$mdot_{well}$ = 0.032 [kg/s]
μ_{br} = 0.004598 [kg/m-s]	$Nuss_{inpodpipe}$ = 3.36	$Nuss_{outsidepodpipe}$ = 3.951	$Nuss_{outsidewellpipe}$ = 3.951
ν_{br} = 0.00000357 [m^2/s]	$PodPipe_{mat}$ = 233.8 [W/m-K]	$Podwall_{mat}$ = 233.8 [W/m-K]	Pod_{fluid} = 0.543 [W/m-K]
$pod_{material}$ = 233.8 [W/m-K]	$Pod_{thickness}$ = 0.01 [m]	Ppod = 262 [kPa]	Pr_{P1} = 23.16
Pr_{W3} = 23.16	Pwell = 344 [kPa]	$P_{workingfluid}$ = 379.2 [kPa]	Q_{ground} = 87.01 [W]
Q_{pod} = 45.25 [W]	Q_{total} = 755 [W]	Q_{well} = 622.8 [W]	Q_{wellR} = 0.008832 [K/W]
Ray_{P1} = 2613	Ray_{W3} = 2613	RG1 = 0.02341 [K/W]	$RG2_{sfactor}$ = 0.0003971 [K/W]
$RG2_{sphere}$ = 0.000003438 [K/W]	RG3 = 0.008377 [K/W]	rp2 = 0.99 [m]	rs1 = 2 [m]
rs2 = 1 [m]	RW1 = 0.002899 [K/W]	RW2 = -0.000002389 [K/W]	RW3 = 0.005935 [K/W]
Rwell = 0.008832 [K/W]	R_{P1} = 0.005935 [K/W]	R_{P2} = -0.000002389 [K/W]	R_{P3} = 0.02059 [K/W]
R_{total} = 0.06753 [K/W]	S = 10.77 [m]	Tground = 10 [C]	Tinpod = 10 [C]
$Tout_{well}$ = 8.341 [C]	Tpodfluid2 = 11 [C]	Tpodliquid = 7.2 [C]	Tpodpipe = 7 [C]
Twellwater = 12.7 [C]	Twellwater2 = 13 [C]	Tworkingfluid = 6 [C]	T_{solved} = 11 [C]
UnitArea = 1 [m]	$U_{overall}$ = 14.81 [W/m-K]	WorkingFluid = 0.09202 [W/m-K]	z = 3 [m]

APPENDIX E: OPTIMIZED EES CODE RESULTS

Unit Settings: SI C kPa kJ mass deg

AG3 = 3.142 [m^2]	α_{br} = 1.541E-07 [m^2/s]	AP1 = 2.749 [m^2]	AW3 = 2.749 [m^2]
β_{br} = 0.0000469 [1/C]	cp_{br} = 2.736 [kJ/Kg*K]	Cp_{meth2} = 4200 [J/kg*K]	Cp_{water} = 4.184 [kJ/kg*K]
Cp_{water2} = 4184 [J/kg*K]	D = 2 [m]	$Di_{podpipe}$ = 0.0229 [m]	$Di_{wellpipe}$ = 0.0229 [m]
$Do_{podpipe}$ = 0.025 [m]	$Do_{wellpipe}$ = 0.025 [m]	$Excel_h$ = 19558 [W/m^2*K]	g = 9.81 [m/s^2]
$Ground_{thickness}$ = 1 [m]	hG3avg = 38 [W/m^2*K]	hG3h = 41 [W/m^2*K]	hG3v = 35 [W/m^2*K]
hP1 = 85.82 [W/m^2*K]	hP3 = 13.5 [W/m^2*K]	hW1 = 1173 [W/m^2*K]	hW3 = 85.82 [W/m^2*K]
h_{forced} = 200 [W/m^2*K]	Kal = 233.8 [W/m-K]	$kcacl2_{br}$ = 0.543 [W/m-K]	$kcacl2_{pod}$ = 0.543 [W/m-K]
Kea = 0.4023 [W/m-K]	Kglyc = 0.4715 [W/m-K]	Kground = 5.03 [W/m-K]	Khe = 0.1446 [W/m-K]
Kk2co3 = 0.548 [W/m-K]	Kmercury = 8.279 [W/m-K]	$Kmeth_{wf}$ = 0.09202 [W/m-K]	kmgcl2 = 0.4463 [W/m-K]
$Knacl_{pod}$ = 1 [W/m-K]	Kox = 0.0253 [W/m-K]	$Kr134a_{pod}$ = 0.01267 [W/m-K]	Kwater = 0.5727 [W/m-K]
$Kwater_{pod}$ = 0.562 [w/m-K]	$L_{podpipe}$ = 35 [m]	L_{well} = 35 [m]	$mdot_{house}$ = 1.3 [kg/s]
$mdot_{well}$ = 0.032 [kg/s]	μ_{br} = 0.004598 [kg/m-s]	$Nuss_{inpodpipe}$ = 3.36	$Nuss_{outsidepodpipe}$ = 3.951
$Nuss_{outsidewellpipe}$ = 3.951	ν_{br} = 0.00000357 [m^2/s]	$PodPipe_{mat}$ = 233.8 [W/m-K]	$Podwall_{mat}$ = 233.8 [W/m-K]
Pod_{fluid} = 0.543 [W/m-K]	$pod_{material}$ = 233.8 [W/m-K]	$Pod_{thickness}$ = 0.01 [m]	Ppod = 262 [kPa]
Pr_{P1} = 23.16	Pr_{W3} = 23.16	Pwell = 344 [kPa]	$P_{workingfluid}$ = 379.2 [kPa]
Q_{ground} = 282.9 [W]	Q_{pod} = 63.34 [W]	Q_{total} = 1594 [W]	Q_{well} = 1248 [W]
Q_{wellR} = 0.004407 [K/W]	Ray_{P1} = 2613	Ray_{W3} = 2613	RG1 = 0.00791 [K/W]
$RG2_{sfactor}$ = 0.0003971 [K/W]	$RG2_{sphere}$ = 0.000003438 [K/W]	RG3 = 0.001592 [K/W]	rp2 = 0.99 [m]
rs1 = 2 [m]	rs2 = 1 [m]	RW1 = 0.0001692 [K/W]	RW2 = -0.000001707 [K/W]
RW3 = 0.004239 [K/W]	Rwell = 0.004407 [K/W]	R_{P1} = 0.004239 [K/W]	R_{P2} = -0.000001707 [K/W]
R_{P3} = 0.01471 [K/W]	R_{total} = 0.03325 [K/W]	S = 10.77 [m]	Tground = 10 [C]
Tinpod = 10 [C]	$Tout_{well}$ = 2.107 [C]	Tpodfluid2 = 11 [C]	Tpodliquid = 7.2 [C]
Tpodpipe = 7 [C]	Twellwater = 12.7 [C]	Twellwater2 = 13 [C]	Tworkingfluid = 6 [C]
T_{solved} = 11.01 [C]	UnitArea = 1 [m]	$U_{overall}$ = 30.08 [W/m-K]	WorkingFluid = 0.09202 [W/m-K]
z = 3 [m]			

APPENDIX F: CONVECTION CORRELATIONS

Source (http://www.brighthubengineering.com/hvac/91056-calculation-of-forced-convection-heat-transfer-coefficients/)

Forced Convection Heat Transfer Coefficient Correlations (S.I. units)

2. Laminar Flow Inside a Circular Tube

Inputs

Fluid =	water	
Ave. Fluid Temp, T_b =	6	°C
Pipe Diam., D =	22.9	mm
Pipe Diam., D = (calculated)	0.023	m
Ave. Velocity, V =	1.3	m/s
Fluid Density, ρ =	995	kg/m³
Fluid viscosity, μ =	0.00079	N-s/m²
Fluid Sp. Heat, C_p =	4.19	kJ/kg-K
Fluid Sp. Heat, C_p = (calculated)	0.58	W/m-K
Fluid Thermal Conductivity, k =	0.00058	kJ/s-m-K
Pipe Length, L =	25	m
Entrance Length, Le = (calculated)	2250	ft

Calculations

Reynolds Number, Re =		37495	
Prandtl Number, Pr =		5.7	
Correlations #1. Fully Developed Flow (Le >> L)			
Const. T_{wall}	Nu_o =	3.66	
	h_o =	334	kJ/hr-m²-K
Const. heat flux	Nu_o =	4.36	
	h_o =	398	kJ/hr-m²-K
Correlation #2 (Pr > 5 ; Le > L):			
	Nu_o =	17	
	h_o =	1528	kJ/hr-m²-K
Correlation #3 (0.6 < Pr < 5 ; Le > L):			
	Nu_o =	11	
	h_o =	985	kJ/hr-m²-K

Equations for Forced Convection Flow inside Pipes

$$Nu = \frac{h\,D}{k} \qquad Re = \frac{D\,V\rho}{\mu} \qquad Pr = \frac{\nu}{\alpha} = \frac{\mu\,C_p}{k}$$

Dimensionless Numbers used in Forced Convection Heat Transfer Coefficient Correlations

Correlations #1: Fully Developed Laminar Flow (L >> Le)

Constant Wall Temperature: $Nu_o = 3.66$

Constant Heat Flux: $Nu_o = 4.36$

Correlation #2: (Le > L)

Thermal or Thermal/Hydrodynamic Entrance Region,
Constant Wall Temperature, $Pr \geq 5$
Laminar Pipe Flow, $Re < 2300$

$$Nu_o = 3.66 + \frac{0.0668\ Re\ Pr\ (D/L)}{1 + 0.04\,[\,Re\ Pr\ (D/L)]^{2/3}}$$

Correlation #3: (Le > L)

Thermal and Hydrodynamic Entrance Region
Constant Wall Temperature - Laminar Flow ($Re < 2300$)
$0.6 < Pr < 5 \qquad 0.0044 < \frac{\mu_b}{\mu_w} < 9.75$

$$Nu_o = 1.86 \left(\frac{Re\ Pr}{L/D}\right)^{1/3}$$

Correction for Temperature Variation: ($h = h_o(\mu_b/\mu_w)^{0.14}$

Inputs

Ave. Fluid Temp, T_b =	6	°C
Fluid Visc. at T_b, μ_b =	0.000785	N-s/m²
Ave. Wall Temp, T_w =	7	°C
Fluid Visc. at T_w, μ_w =	0.00057	N-s/m²

Calculations

Correlations #1. Fully Developed Flow			
Const. T_{wall}	h =	349	kJ/hr-m²-K
Const. heat flux	h =	416	kJ/hr-m²-K
Correlation #2 (Pr > 5):			
	h =	1598	kJ/hr-m²-K
Correlation #3 (0.6 < Pr < 5):			
	h =	1030	kJ/hr-m²-K

Velocity Iteration

Avg. Vel	h
1	1309
2.5	2750
5	5151
7.5	7552
10	9953

NOTE: The spreadsheet calculates the forced convection heat transfer coefficient, h, for each of the three correlations. You need to choose the correct one to use. In this case, Correlation #2 is the correct one, because Le > L and Pr > 5.